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SPRAY NOZZLE DESIGNS FOR AGRICULTURAL AVIATION APPLICATIONS.(U)

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by K. W. Lee, A. A. Putnam, J. A. Gieseke,
M. N. Golovin and J. A. Hale

BATTELLE
COLUMBUS LABORATORIES

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16. Abstract

ONE OF THE DIFFICULT PROBLEMS IN THE FIELD OF AGRICULTURAL AVIATION IS TO ACCURATELY AND UNIFORMLY APPLY CHEMICALS TO TARGET AREAS. AN ATOMIZER CAPABLE OF PRODUCING UNIFORM DROPS HAS A HIGH PROBABILITY OF OVERCOMING THIS PROBLEM. A COMPREHENSIVE LITERATURE SURVEY WAS PERFORMED ON EXISTING TECHNIQUES FOR GENERATING A SPRAY OF UNIFORMLY SIZED DROPS AND ON INFORMATION REGARDING CHEMICALS CURRENTLY USED IN AGRICULTURAL AVIATION SPRAY APPLICATIONS. IN ADDITION, NEW CONCEPTS FOR PRODUCING A UNIFORM SPRAY WERE GENERATED AND CONCEPTUALLY DESIGNED. THE RESULT OF THE LITERATURE SURVEY SHOWS THAT AMONG THE AVAILABLE TECHNIQUES, PERIODIC DISPERSION OF LIQUID JET, SPINNING DISK METHOD, AND ULTRASONIC ATOMIZATION ARE MOST PROMISING, IN THAT ORDER. SUBSEQUENTLY, IDEAS FOR THREE ADDITIONAL, PREVIOUSLY UNTRIED TECHNIQUES WERE GENERATED. THESE ARE BASED ON CLASSIFICATION OF THE DROPS USING CENTRIFUGAL FORCE, ON USING TWO OPPOSING LIQUID-LADEN AIR JETS, AND ON OPERATING A SPINNING DISK AT AN OVERLOADED FLOW. ESTIMATES OF OPERATIONAL CHARACTERISTICS WERE MADE, BUT DUE TO THE PREDICTIVE AND EXPLORATORY NATURE OF THE PROPOSED TECHNIQUES, EVENTUAL VERIFICATION OF THE SOUNDNESS AND PROBABILITY OF EXTENDING THE PROPOSED TECHNIQUES INTO A PRACTICAL ATOMIZER MAY REQUIRE EXPERIMENTAL TESTS ON A LABORATORY SCALE.

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FINAL REPORT

on

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to

NASA, LEWIS RESEARCH CENTER
Contract NAS3-21581

September 18, 1979

by

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EXECUTIVE SUMMARY

It was proposed that an atomization technique be developed for producing a spray of uniformly sized drops in order to avoid the usual drift of agricultural pesticide chemicals to nearby crops or susceptible animals if applied aerially from an aircraft. As a first step to pursue this approach, comprehensive literature surveys were performed on both existing techniques for generating such a uniform spray developed for other applications and the information regarding chemicals currently used in agricultural aviation spray applications. Subsequently, the surveyed information was technically assessed. In addition, new concepts for producing a uniform spray were generated and conceptually designed.

As a result of the literature surveys, approximately 15 different techniques were identified. Among those techniques, periodic dispersion of liquid jet, spinning disk method, and ultrasonic atomization were assessed to be most promising, in that order. While these techniques have a high probability of being developed into the one for agricultural purposes, all of them were found to require some extension of their flow rate capabilities to match those required in current agricultural aviation applications.

As a second phase of the study, ideas for three additional previously untried techniques were generated and developed into conceptual designs. The first technique would operate on the principle under which the drop sizes of an initial spray with a wide drop size distribution are truncated to produce a more uniform size distribution. A classification of the drops using a centrifugal force field was proposed for this technique and a theoretical correlation predicting the drop size with respect to design parameters and operating conditions was given. The second concept is based on two opposing liquid-laden air jets colliding in an acoustically active region. Due to decelerated and accelerated flows resulting in this region, large drops have to undergo more breakup stages than small drops. This improves the size distribution. The third idea is to design a device similar to the conventional spinning disk atomizer but operate it at an overloaded flow. The sheet of liquid initially produced this way is to be broken up by imposing an external sonic vibration.

Due to the predictive and exploratory nature of the present study, it would be rather premature to predict the actual performance of the conceptual designs without any supporting experimental data. Consequently, eventual verification of the soundness and probability of extending the proposed techniques into a real atomizer for a practical use may have to be achieved only by experimental tests on a laboratory scale.

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INTRODUCTION

The use of aircraft for applying the chemical formulations to control agricultural pests is considered cost competitive when compared to other application methods and is usually the best method when time restrictions exist. However, one of the difficult problems in the field of agricultural aviation is the accurate and uniform application of chemicals to the target areas while avoiding the drift of chemicals which might damage nearby crops or present hazards to susceptible animals and people in the vicinity. Considering the size distribution of these droplets or particles, a loss of material occurs at both the large and small size ends. While excessively large drops settle directly on the ground resulting in a nonuniform deposit, small droplets can drift away. In order to eliminate these problems, the drop size has been controlled in the past by changing the liquid properties such as viscosity, density, and surface tension by use of chemical additives. While the size of individual drops themselves can be varied to a certain extent, this approach does not provide a uniformity of drop sizes. One of the logical solutions to this problem is then to develop an atomization technique that can produce monodisperse sprays. Considering that various dynamics of spray

drops such as settling, drifting and vaporization are strongly dependent upon their size, this approach has a high potential for overcoming many spray application problems.

The objective of the first phase of the present program was to perform comprehensive literature surveys on the techniques of generating monodisperse sprays and on the information concerning liquids used in agricultural aviation spray applications. The objective of the second phase of the program was to conceptually design and assess spray nozzles for generating monodisperse sprays. Major emphasis was given to generating new atomization concepts that have not been used previously in any application. Thus, any generated concepts were to be conceptual rather than extensions of existing spraying techniques to agricultural applications.

This report covers technical efforts for both the literature survey and conceptual design phases of the program which were conducted during the period from October, 1978 to February, 1979, and from March to August, 1979, respectively. The pertinent literature references identified during the first phase are listed alphabetically in the Bibliography regardless of whether or not they are cited in this report.

PERFORMANCE REQUIREMENTS FOR SPRAY NOZZLES

The ultimate objective of the current program is to identify or to generate a new concept for producing monodisperse sprays. Throughout the program, emphasis has been given to the fundamentals or basic principles that can satisfy the requirement of producing a monodisperse spray. Other important requirements have been the ranges of drop size and physical properties of sprays. Liquid flow rates that can be covered by each technique have also been given important consideration. In establishing criteria for the above requirements, results of a literature survey of agricultural aviation industry are to be used. Finally extension of the range of applicability of the technique and eventual development for agricultural application are to be assessed based on the collected information on the current state of the art for each technique.

Specific requirements to be met by the extended ability of the identified techniques are:

(1) Monodispersity of sprays: preferably only 5 percent by weight of the drops should be larger than a maximum size and only 5 percent smaller than a minimum size where the maximum and minimum are defined respectively as 1.2 and 0.80 times the average diameter.

(2) Average drop size: the nozzle should produce sprays over the size range currently employed for aerial applications.

(3) Range of liquid properties: the nozzle should perform satisfactorily over the range of liquid properties currently used in agricultural applications.

(4) Application rate: the spraying system should be capable of covering the range of flow rates that is currently used in agricultural application.

In addition to the performance requirements listed above, there are the following requirements for the nozzles to be developed for agricultural aviation applications:

(5) Ease of operations and controls, including initiation and shutoff

(6) Low power requirements

(7) Light weight and small dimensions

(8) Immunity to variable weather conditions

(9) Low cost

(10) Short development time.

Assessment of the priority level for each of the above requirements will be discussed further later.

MONODISPERSE SPRAY PRODUCING TECHNIQUES

Means for producing sprays of uniformly sized droplets have recently been subject of interest for a variety of research and industrial applications such as Xerography, paint spraying, mass spectroscopy, combustion, and polymer coating. Monodisperse sprays are also needed as test droplets for evaluating the performance of various dust control devices such as cyclones, filters, and wet scrubbers. In calibrating dust counting devices, not only are such test droplets required to attain a good monodispersity, but their droplet sizes are to be accurately determined.

In this section, the techniques for producing sprays of uniform drop are introduced. Emphasis will be given to those capable of producing a monodisperse spray, although the techniques which have a potential for development into a more refined form are included. Among the identified techniques, those which have been proven not useful are either not included in the discussion or only briefly mentioned. Only the basic principles and concepts behind each technique are described in this section. Further assessment of the theoretical limits and range of operations for the selected techniques will be made in the separate section, under the heading of "Assessment of the Current State of the Art".

Periodic Vibration of Liquid Jet

This technique is based on the instability of a liquid jet emerging from a capillary tube or an orifice. If a liquid stream is emitted from the tube under pressure, this stream is by nature unstable and will soon disintegrate into droplets by the action of any external forces. The collapse of such a stream into very uniform droplets is attainable with the application to the stream of a periodic vibration of suitable amplitude and frequency. The necessary vibrations can be successfully obtained by using (1) a piezoelectric transducer, (2) an acoustic vibration, or (3) a direct mechanical means. These different types of vibrations will be discussed separately. It is necessary to

divide this technique into the three categories because each of the three categories or types differs not only in design but also in the drop size range that can be covered.

Electrostrictive Disk Type Generator

Disintegration of liquid stream emerging from an orifice can be precisely controlled if the orifice is vibrated periodically. Such a periodic vibration of the orifice can be achieved by implanting the orifice into a disk made of electrostrictive material (piezoelectric crystal) and by applying an electrical signal to the piezoelectric crystal. The performance of apparatus based on this type of design has been experimentally studied by Ström (1969)* and Berglund and Liu (1973).

Figure 1 is a schematic diagram of the droplet generating system. The system consists of a liquid feeding line, a vibrating orifice and a signal generator which provides the necessary disturbance to the orifice. As will be further discussed, size of the droplets generated by the apparatus depends upon the orifice size, liquid velocity, and the signal frequency.

The frequencies of piezoelectric crystals generally range from about 10 to 1000 kHz and the sizes of the droplets produced in this frequency range are about 3 to 50 μm. The orifice diameter normally ranges from 3 to 20 microns.

When a monodisperse spray of relatively small droplets are to be produced, small orifices are needed. One of the operational problems in using such small orifices is that the orifice is easily clogged even by a small amount of solid particulates present in the liquid. In order to avoid this problem, it is usually required to purify the liquid before feeding into the orifice. For this purpose, membrane filters are installed as illustrated in Figure 1. In this case, these filters have to be periodically replaced. Another problem is that droplets initially very uniform in size can agglomerate soon after

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* Names and dates in parentheses refer to Bibliography at end of report.

leaving the orifice. It is therefore necessary to provide a dilution airflow around the orifice such that the produced droplets are immediately dispersed.

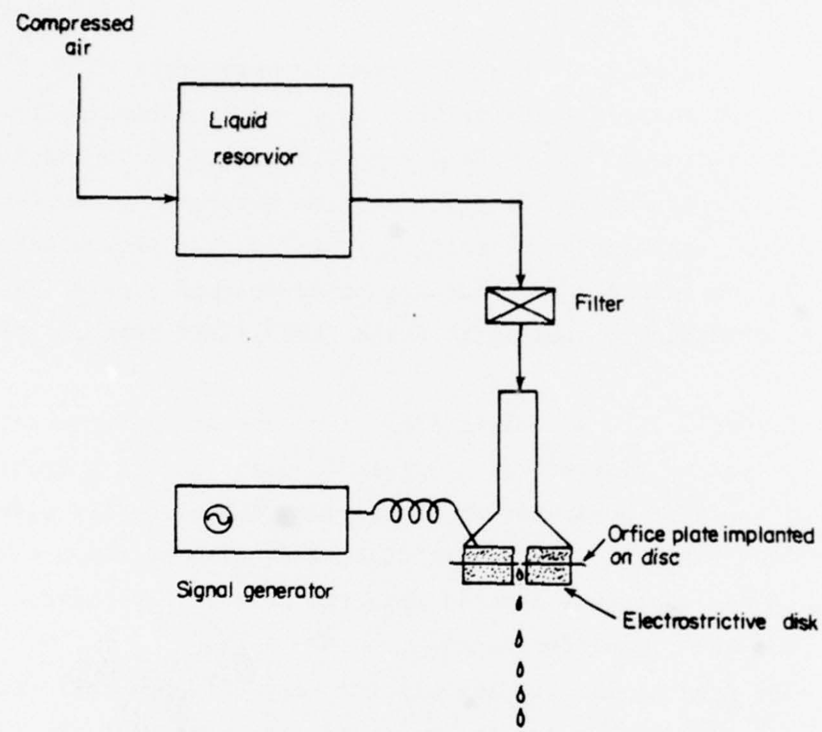

FIGURE 1. SCHEMATIC DIAGRAM OF ELECTROSTRICTIVE DISK TYPE GENERATOR

Vibrating Tube Using Audio Signal

Instead of using the electrostrictive orifice vibrated periodically by an electrical signal, a liquid jet can be passed through a tube of relatively large diameter. The vibrations can be imparted onto the tube in the form of an acoustic wave using an audio speaker. This type

of arrangement was studied by Rajagopalan and Tien (1973), and Magarvey and Taylor (1956). A schematic diagram of the necessary apparatus similar to that used by Rajagopalan and Tien (1973) is shown in Figure 2. The liquid contained in the liquid reservoir is forced to leave a capillary tube by pressurized gas cylinder. The necessary vibration to the tube is transmitted by the metal rod connected to an oscillator. Thus, the signal generated by the oscillator, and subsequently amplified is transmitted to the metal rod which is connected to the speaker diaphram.

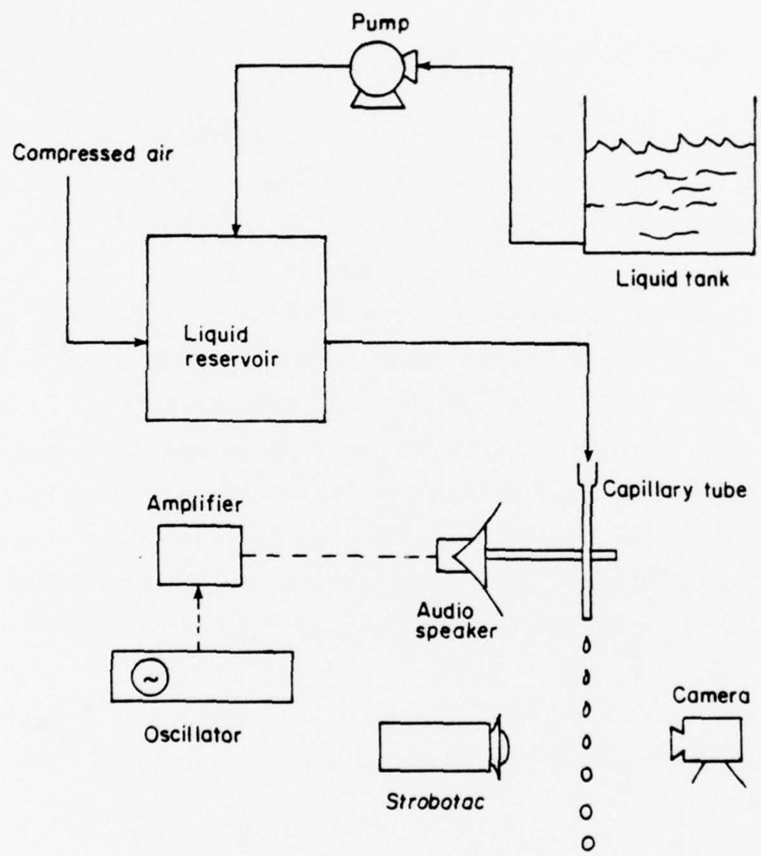

FIGURE 2. SCHEMATIC DIAGRAM OF VIBRATING-TUBE SPRAYER USING AUDIO SIGNAL

The diameter of the capillary tube normally ranges from 50 to 1500 μm, thus, much larger than that for the electrostrictive disk. The resulting droplet size lies between 100 to 3000 μm in diameter. The signal frequency is in the range of 0.5 to 30 kHz. It is reported that the observed drop size always agrees with the calculated drop size. The formula for this calculation will be discussed later. The monodispersity of the sprays as reported by the investigators is exceptionally good. For example, Magarvey and Taylor (1956) report that the standard deviation of the droplets from the mean value is less than 0.5 percent for the mean size up to 10,000 μm.

Vibrating Tube Using Mechanical Means

Another way to produce a periodic disturbance in the liquid jet is the use of some sort of mechanical means. Binek and Dohnalová (1967) used a fine whisker dipped periodically into the liquid reservoir. The schematic design of the generator is shown in Figure 3. The whisker shown in the figure is connected to a flat spring of silicon iron which is vibrated by an electromagnetic field. The 50 Hz AC current was used to create the magnetic field. The whisker has a round shaped tip of 0.015 mm in diameter. They observed that when the whisker emerges above the liquid surface, initially a "liquid bridge" is formed across the whisker tip and the liquid surface. As the whisker moves up further, this bridge is separated to form a droplet. They found that the immersion depth of the whisker as well as liquid surface tension and viscosity can determine the droplet size.

A similar attempt may be made by employing a periodically rotating needle which can break up the liquid jet emerging from a capillary tube.

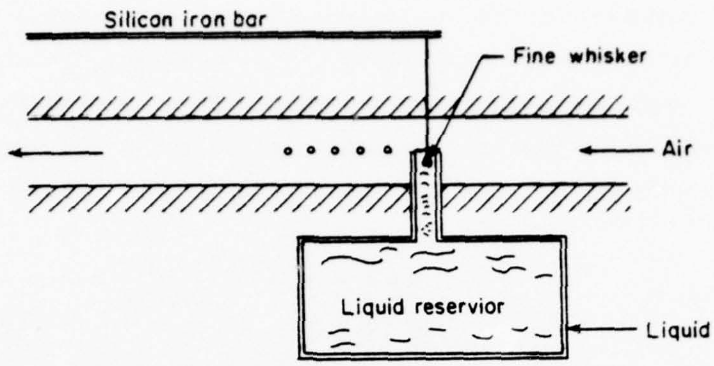

FIGURE 3. SCHEMATIC DIAGRAM OF VIBRATING TUBE SPRAYER USING A WHISKER

Other Types of Vibrating Tube

There can be many other types of variations of the periodic dispersion of liquid jet depending upon the particular applications. Erin and Hendrick (1968) utilized the vibrating tube configuration coupled with an earphone to produce the electrically charged solid particles. In order to obtain uniform liquid droplets in the form of suspension in another liquid system, Fulwyler, et al (1973) introduced a sheath liquid around the liquid droplets which were produced by a piezoelectric transducer.

Periodic Vibration of Liquid Reservoir

Disintegration of liquids in a manner similar to that described above can also be achieved when the vibrations are applied to the liquid reservoir rather than to the orifice or tube, as demonstrated by Fulwyler and Raabe (1970). Thus, the reservoir wall or the bottom could be made of piezoelectric crystal such that the pressurized liquid contained in this type of reservoir can be squirted out through an orifice to produce uniform droplet at each frequency. A schematic diagram of this type of nozzle is shown in Figure 4.

Although there is a distinctive difference in configuration and design between this technique and the vibrating orifice/tube atomizers, both of these techniques may be considered similar in that individual drops are periodically produced by an externally controlled disturbance. Therefore, further discussion on the periodic vibration of liquid reservoir will be combined with that for liquid jet.

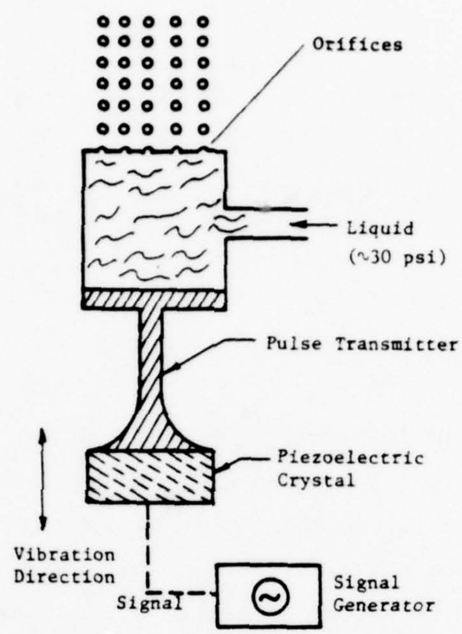

FIGURE 4. SCHEMATIC DIAGRAM OF VIBRATING RESERVOIR ATOMIZER

Electrostatic Atomization

For certain liquids, electrostatic dispersion provides another method for producing uniform droplets. If a high electrical potential is applied to a liquid contained in a reservoir, the stream of liquid which would normally flow slowly through the nozzle on the reservoir will be disintegrated into fine droplets. As the applied electrical voltage is increased, the droplets become smaller and the jet velocity

also increases. In general, if the voltage is increased further, the liquid jet would disappear forming a spontaneous atomization of liquid to form a fine mist at the nozzle.

Figure 5 shows schematically the dispersion of a liquid at several electrical potentials as observed by Drozin (1955). When a low electric voltage is applied to the liquid as shown in Figure 5(b), he found that the droplet production rate was increased. As the electric voltage is further increased as in Figure 5(c), there exists a stream of liquid appearing as a thread. Finally, at a high voltage this thread disappears leaving a cloud of fine droplets as shown in Figure 5(d).

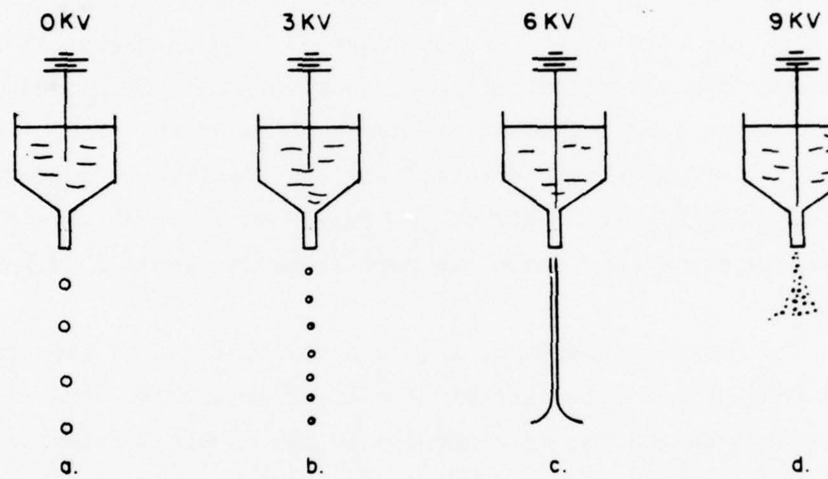

FIGURE 5. ELECTROSTATIC ATOMIZATION OF LIQUID SHOWING DISPERSION OF LIQUID AT DIFFERENT APPLIED VOLTAGES (Drozin, 1955)

The term "electrostatic atomization" can cover a variety of different processes with respect to flow rate, electric potential and droplet size. The process involving a flow rate of up to 3 ℓpm with a single nozzle using a voltage on the order of 100 kv has been applied for electrostatic paintings in industry. A similar technology has been used for manufacturing a printed circuit in the electronic industry. The applied voltage in this case is on the order of 10 kv and the

corresponding flow rate is extremly small. This process is generally performed in a vacuum. Significant work on electrostatic atomization has also been done for oil burner applications.

Many different observations have been made which may be used to explain the droplet formation mechanisms associated with electrostatic atomization. Vonnegut and Neubauer (1952) atomized water, sugar solutions, lubricating oil, and alcohol. They observed that there was an upper limit of liquid electrical conductivity beyond which no atomization could be achieved. Also they found that monodisperse sprays were not formed with the negative potential on the liquid. A similar experimental observation has been made by many investigators such as Zeleny (1914), Macky (1931), Bollini, et al. (1974), and Nawab and Mason (1958). Generally, they observed that the electrical voltage required to disintegrate the liquid jet depends on the electrical property of the liquid. For example, fine mists can be produced using liquids such as water, alcohol and dibutyl phthalate, all of which have a relatively low electrical conductivity. However, some organic liquids such as benzene and carbon tetrachloride, which have low dielectric constants were found difficult to disperse by this method.

The basic mechanism of liquid disintegration by electrostatic charge is that when a high electrical voltage is applied, the liquid becomes highly charged and pressure due to the electrostatic forces increases. When this pressure exceeds the surface tension, the liquid surface becomes unstable. Because of the rather complex physics involved in the droplet dispersion mechanisms, no firm theoretical models have been established yet. Pfeiffer's (1973) model is such that the dispersion of the liquid by electrostatic atomization takes place due to the detachment of a single drop from the capillary tip. However, this model has not been proven experimentally.

Ultrasonic Atomization

This technique is based on the principle that a liquid droplet is produced when powerful, high frequency sound waves are focused onto the liquid surface. The liquid may be present in large volumes and contained in a reservoir, but the technique can also be applied to very thin films. A schematic diagram of this type of atomizer is shown in Figure 6. In general, a certain form of concave reflector such as a curved barium titanate transducer is used for this purpose. The wave propagation generated by the transducer is then transmitted into the liquid. If this wave strength is greater than the surface tension, the liquid is disintegrated.

The droplet formation mechanism in this type atomizer has been generally considered to be due to the formation and subsequent collapse of cavities caused by the intensive wave. However, Hidy and Brock (1970) stated that the surface of a liquid over an acoustic transducer generally appears to be a layer. If the amplitude of the ripple on this layer becomes large, these crests may break to form droplets. Thus, they further stated that the droplet size would be related to the ripple wavelength which in turn is controlled by the vibration frequency.

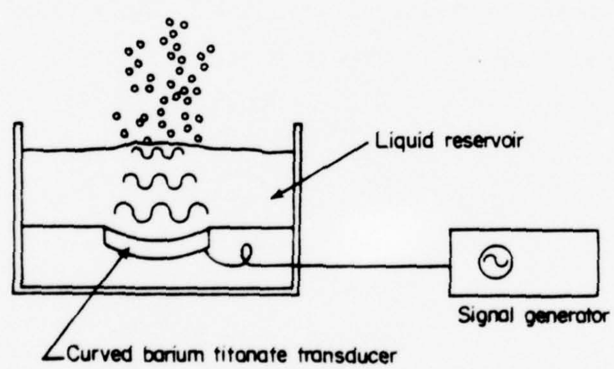

FIGURE 6. SCHEMATIC DIAGRAM OF ULTRASONIC ATOMIZER

Spinning Disk Method

Spinning disks and tops produce droplets of moderately uniform size by feeding a liquid onto a rotating disk from which the liquid is dispersed radially into small droplets by the centrifugal force. In general, liquid is fed to the center of the disk and flows to the edge where it accumulates until the centrifugal force, which increases with increasing liquid at the edge, overcomes the surface tension and disperses the liquid. A schematic diagram of the spinning disk is depicted in Figure 7.

The spinning disk and top have probably been the most generally successful methods for producing monodisperse sprays. One operating problem is that this dispersion produces undesirable secondary sprays (satellite droplets) as shown in the figure. However, these satellite droplets can be separated dynamically from the larger primary droplets. This is usually done by a separate flow of air near the disk, into which the satellites move but beyond which the larger primary droplets are thrown.

The spinning disk method is capable of producing a moderately monodisperse spray over a wide range of drop size. The mean drop size depends upon the surface tension of liquid, liquid density, disk diameter and rotational velocity of the disk. The average drop size ranges approximately from 10 to over 200 μm.

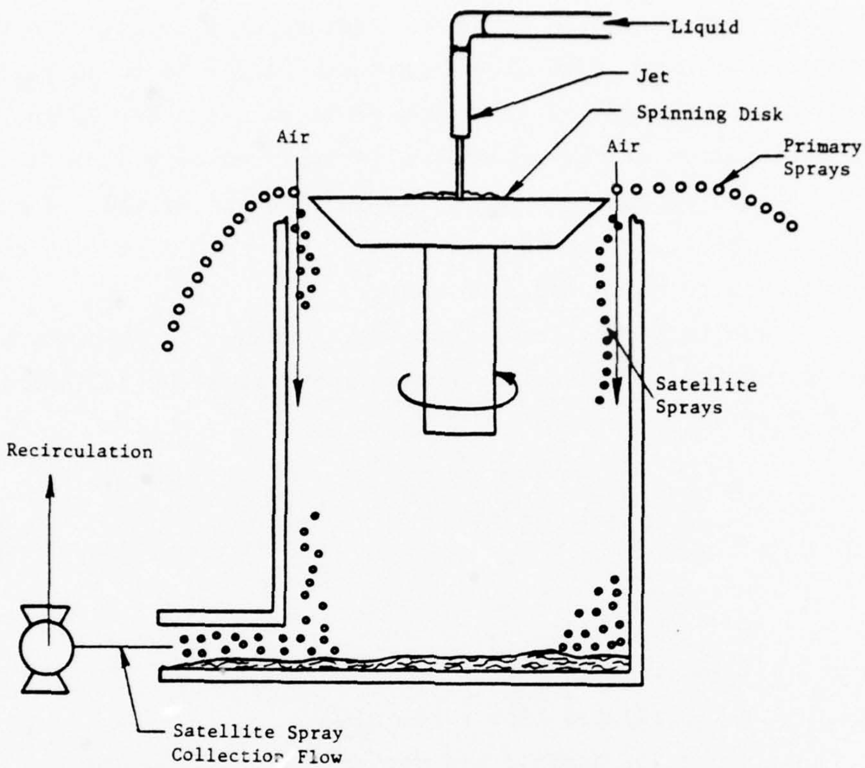

FIGURE 7. SCHEMATIC DIAGRAM OF SPINNING DISK WITH A SECONDARY FLOW FOR REMOVING SATELLITE DROPLETS

Vaporization-Condensation Technique

This technique involves atomizing the liquid, vaporizing it, and then subsequently condensing the vapor. The liquid formed is generally atomized by a pressure atomizer. Since the spray initially produced in this way is polydisperse, the spray is vaporized by heating it above the boiling point of the liquid, usually by a combustor or an electrical heater. Then the vapor is mixed with a stream of hot air containing a regulated number of condensation nuclei. The mixture of air vapor and nuclei passes through a section in which it is slowly cooled, becoming supersaturated and condensing uniformly upon the nuclei to form uniform droplets.

This technique is currently in use for spraying certain insecticide chemicals. As a heating source, a pulse jet or a reciprocating engine is used. The liquid capacity ranges up to 40 gallons per hour. No data on droplet size or monodispersity are available, however. Another application of this technique is for producing a cloud of smoke for the military purpose of camouflage in the battlefield. For obscuration in the light wavelength range of 0.4 to 0.8 μm, the droplet size is desired to be in the same range.

A qualitative size estimate may be made for droplets produced by the evaporation/condensation technique by using the following experssion of Langmuir (1942),

$$D^3 = \frac{38.4\ Z\ Q^{1/2}}{(1 + m_o)^{3/2}\ v^{3/2}} \tag{1}$$

where

D = particle diameter, cm

Q = liquid mass flow rate, g/sec

m_o = mass of admixed air per unit mass of liquid

Z = function of the heat content of the vapor escaping from the nozzle

v = velocity, cm/sec.

It should be noted that the drop size depends on the heat content of the vapor. His expression, however, does not include the number of nuclei which is generally known to be an important factor in determining the drop size in the condensation process.

Miscellaneous Techniques

Atomization of a Solution

If a relatively nonvolatile liquid is dissolved in a volatile solvent and the solution is atomized, the solvent material will evaporate upon encountering the surrounding air, thus, leaving only the nucleus

droplets consisting of the nonvolatile solute. This technique requires that the liquid to be dispersed be mixed or dissolved in a solvent, thus being limited to the use under the above requirement. If the original droplet diameter before evaporation is d_o and the solution density is ρ_o, the final nucleus droplet size is calculated by the following mass balance equation

$$\frac{\pi}{6} \rho_o d_o^3 \chi = \frac{\pi}{6} D^3 \rho \qquad (2)$$

so that

$$D = d_o \left(\frac{\chi \rho_o}{\rho}\right)^{1/3} \qquad (3)$$

where χ is mass concentration of the solution and ρ is the density of final droplets. It should be noted that this technique in general does not provide a good monodisperse spray although the mean size may be changed.

A similar technique has been applied to the atomization of monodisperse suspensions in water. This type of method first used in the medical field is now widely used to spray monodisperse solid particles such as polystyrene latex particles manufactured by the Dow Chemical Company. Salt, sugar and methylene blue dye dissolved in water also have been used to form aerosols of the solute material. One precaution that should be taken is to keep the concentration of such solid particles in the solvent relatively low to avoid possible agglomeration of suspensions in the solvent.

Aerodynamic Atomization

In this type of atomization, compressed air is used to break up the liquid into droplets. For this reason it is often called the air-blast type atomizer or the two-fluid nozzle. This method is probably one of the simplest and the most commonly used for producing droplets for use in many areas such as medicine, combustion, and agriculture. Breakup of liquid is primarily achieved by the complex interaction between liquid and air. Green and Lane (1957) qualitatively explained the liquid breakup

mechanism involved in aerodynamic atomization by dividing it into three stages. The first stage is an instability of liquid surface due to various aerodynamic and shear forces creating small ripples. Then these ripples are transformed further into fine ligament which are separated from the main stream of liquid. Finally, these ligaments eventually form droplets due to the surface tension.

Although these qualitative explanations appear simple, the nature of the actual disintegration is very much complex and it is very difficult, if not impossible, to model the complete picture of the disintegration mechanism even for a simple configuration. Due to the complexity, the size of the droplets formed by the aerodynamic atomization is very widely dispersed.

There are many theoretical analyses for predicting the mean droplet size (Rizkalla and Lefebvre, 1975; Garner and Henry, 1953; Ingebo and Foster, 1957; Wigg, 1964; Nukiyama and Tanasawa, 1939). Based on many experimental test results for small air-blast atomizers, Nukiyama and Tanasawa suggested that the mean volume/surface diameter, D_o in micron, can be written as

$$D_o = \frac{585}{(u-v)} \left(\frac{\sigma}{\rho}\right)^{1/2} + 597 \left(\frac{\mu}{\sqrt{\sigma\rho}}\right)^{9/20} \left(\frac{1000Q_L}{Q_G}\right)^{3/2} , \quad (4)$$

where

u = air velocity, m/sec

v = liquid velocity, m/sec

σ = liquid surface tension, dyne/cm

ρ = liquid density, g/cm^3

μ = liquid viscosity, g/cm sec

Q_L/Q_G = flow rate ratio of liquid to gas.

The conditions under which Equation (4) is valid are known to be as follows

$$20 < \sigma < 70 \text{ dyne/cm}$$
$$0.005 < \mu < 0.5 \text{ poise}$$
$$0.7 < \rho < 1.2 \text{ g/cm}^3 .$$

A rather large number of equations to represent drop size distribution have also been suggested by various investigators. However, most of the work was based on efforts to obtain good fits between experimental sets of data and empirical equations. Further, both the predicted and the measured dispersion of the sprays produced by aerodynamic atomization is quite poor. For this reason, no further discussions will be made regarding this type of technique.

Swirl Atomizers

In addition to the spinning disk atomizer, the swirl chamber type makes use of centrifugal forces. This type of atomizer consists of a conical chamber with a small orifice at the vertex. Generally, liquid is introduced tangentially and allowed to swirl. If liquid pressure is high enough, a vortex is created and the liquid leaves the chamber as an unbroken film with a tulip or cone shape, depending on the pressure. If pressure is sufficiently high, the liquid breaks up into droplets. Green and Lane (1957) stated that surface tension, viscous forces and the interaction of the liquid with surrounding air are the main controlling parameters to disintegrate the liquid into droplets.

Watson (1948) showed the effects of pressure and chamber dimensions on the droplet size. According to his data, the smaller the swirl chamber becomes, the finer the droplets that result. However, the flow limits are quite restrictive if small drops are to be formed. Another undesirable characteristic is the inability to get sharp cutoff of spray due to dribbling.

Atomization Using Liquefied Gas

Sprays of fine mists can also be generated by first mixing a liquid with liquefied gas under pressure and then expanding the mixture through a nozzle as used in many applications such as for commercial aerosol cans. Despite the wide use of this technique, very few

systematic studies are available regarding the mean droplet size and the monodispersity. Liu (1967) measured the size distribution of sprays obtained on several samples of cans containing small amounts of dioctylphthalate and freon gas. The measured size distribution was found to be spread rather widely. Further, he found that the mean droplet size was below 1 μm. He also found that the mean droplet size cannot be controlled by the pressure. It is not known how the droplet size can be increased if an increased amount of liquid is mixed with a gas propellant or if the nozzle design is changed.

Whistle Type Atomizers

Although similar to the ultrasonic atomizers using a transducer, liquid can also be disintegrated by directing high pressure gas into the center of a liquid jet, thus creating strong sound waves inside the nozzle, as shown in Figure 8. Due to the sound field created by the focusing air flow, this type of atomizer is frequently called the whistle or stem-cavity type atomizer. This type of atomizer is generally operated at a sound frequency of about 10 kHz with a resulting liquid droplet size on the order of 50 μm.

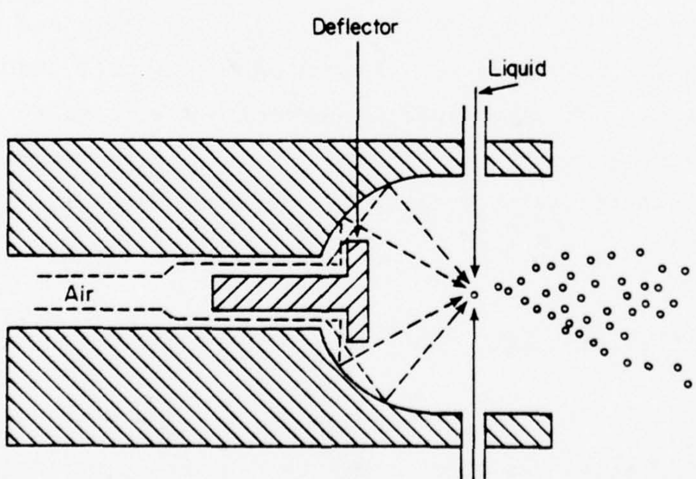

FIGURE 8. SCHEMATIC DIAGRAM OF THE WHISTLE TYPE ATOMIZER SHOWING THE SOUND RESONANCE CAVITY

Many commercially manufactured atomizers of this type are available including those by Astrobeam, Inc., Sonic Development Corp., and Vapo Products, with flow rates up to 1200 gph. One of the disadvantages in these atomizers is that the drop size cannot be easily controlled unless the nozzle dimension is changed. Wilcox and Tate (1965) studied this type nozzle systematically and concluded that the sound field was not an important variable in the atomizing process. Topp and Eisenklam (1972) therefore, suspected that all the whistle atomizers simply operate on a similar principle used in two-fluid types. As discussed previously, a liquid is integrated primarily by the aerodynamic interactions between gas and liquid in the twin-fluid atomizers. No reliable or proven theoretical analyses on the performance of the whistle atomizers seem to be available.

Atomization Using Spark-Discharge

By introducing electrodes inside the liquid level and applying a high potential across the electrodes, the liquid is known to disintegrate into fine droplets due to the spark-discharge. A small scale experiment was performed by Andrus and Walkup (1963) to investigate this phenomena primarily for a domestic burner application. Droplets having the mass median diameter of about 100 μm droplets could be produced. However, the results were reported to be rather erratic and not reproducible. The sizes of the produced sprays were also found to be quite widely dispersed.

AGRICULTURAL AVIATION SPRAY APPLICATIONS

This section reports the information collected from the literature survey on the properties of liquid material, and the ranges of drop size and application rate commonly employed in agricultural aviation spray applications. The type of chemicals, drop size, application rate and properties of the liquid will be discussed in that order.

Pesticide Formulation Types

Pesticides as a general term is used to describe a number of different insecticides, herbicides, fungicides, etc. Most of the original chemicals used for pesticides take the form of either solid or liquid and then are dissolved or mixed in a liquid. Depending upon the phases of the original material, they could be grouped into concentrated solutions, water soluble powders, water dispersible powders, and emulsifiable concentrates.

The concentrated solutions are the liquid chemicals which are dissolved in water. One advantage to the solution formulations is that they are always considered to be homogeneous. Chemical powders which are soluble in water can be formulated into concentrated aqueous solutions with the same advantages as the solutions just described. Wettable or water dispersible chemical powders are those that are not considered to be soluble in water. Therefore, wettable chemical powders generally require agitation after mixing, until they are sprayed. Some powders come in the form of very fine or colloidal size and, therefore, will remain in suspension and require no agitation. Pesticides as emulsifiable concentrates usually consist of organic solvents containing the active ingredients which are then combined with emulsifiers before being added to water. Concentrations of this form will not separate, requiring no agitation before they are applied.

Most pesticide chemicals which come in one of the above forms are further diluted with an inert carrier. Carriers offer the advantage of easy addition of spreading agents to the pesticide as well as wetting

agents and deposit builders. A carrier also reduces the amount of active chemical ingredient required to obtain the same level of efficiency, and favors dilution to as great a degree as is reasonably possible.

Water is found to be the most common carrier used owing to its low cost, safety and ease of application. Another common carrier is oil; and with the many different types available, a variety of solutions may be developed. Foam sprays are sometimes used for pesticide application, providing additional advantages over common carriers. The pesticide is dispersed or dissolved in an aqueous alkali metal silicate foam and can be applied as droplets or as a continuous layer. The advantages of the foam sprays include a low liquid volume requirement, accurate placement of the pesticide, the reduction of drift, clear visibility on the target, and good adherence (Hanson, 1973).

As already discussed, formulations may also contain supplemental additives such as adjuvants and diluents. Some adjuvants, that is emulsifiers, that are largely inert but will often influence physical properties, include wetting and spreading agents, adhesives, and emulsifiers. These additives are used for lowering the surface tension of the liquid, allowing for easy dispersion and easier spreading (DeOng, 1953).

Considering major crops being produced across the United States, the prohibitively large number of currently available pesticide types have been narrowed to those most commonly used. With the aid of statistics from the National Agricultural Aviation Association (Collins, 1979), Table 1 was compiled.

TABLE 1. MOST COMMONLY USED PESTICIDES IN U.S.

Insecticides	Herbicides	Fungicides
Toxaphene	Trifluralin	Balan
Methyl parathion	DSMA and MSMA	Sulfur
EPN	Propylene	
Carbofuran	Ordram	
Disulfoton	2,4-D	
Parthion	Atrazine	
Carbaryl	Propachlor	
Malathion	Alachlor	
	Toxaphene	

Drop Size

Adequate drop size which is desired for aerial applications is found to be dependent on many factors, such as the type of insects, plant or fungus. In addition, aircraft speed and altitude, toxicity of the chemicals, and weather conditions contribute to determining the optimum drop size. All these factors can, however, be further narrowed down into two general categories, one for maximizing the effectiveness of pesticides which is primarily governed by the types of insects or crops, and the other for minimizing the drift which otherwise can cause damages to any susceptible species nearby. The drift also results in a loss of the chemicals.

For an obvious reason, spray effectiveness is largely determined by drop size. Many studies on the optimum drop size under various conditions have been performed (MacQuaig, 1962; Burnett, 1962; Mount, 1970). Akesson and Yates (1974) stated that the most effective drop size for insecticides depends on the insect size. Smaller droplets are more active in the gut of insects and also in external contact. Smith and Goodhue (1942) found that droplets of less than 25 μm are most effective for controlling small instar of mosquito larvae. For larger insects like locusts, drops of about 100 μm were found to be more effective (MacQuaig, 1962). The drop sizes that were found effective from some selected research for several insects are shown in Figure 9.

Another important consideration for spray effectiveness is the depth of penetration inside crops or forests, or the ability of drops to be deposited on breeding sites or plant foliage. According to the particle dynamics, the drop inertia should be minimized for maximizing the effects. Therefore, drop size is preferred to be smaller than about 100 μm. Especially this is found to be true for the forest applications regardless of the type of insects. Indeed, a recent test (NASA, 1977) indicates that for a pesticide which depends upon contact for effectiveness, droplets or particles should range from about 75 to 100 μm in diameter. For application of pesticides by "ultra low volume rates" under which formulated pesticides

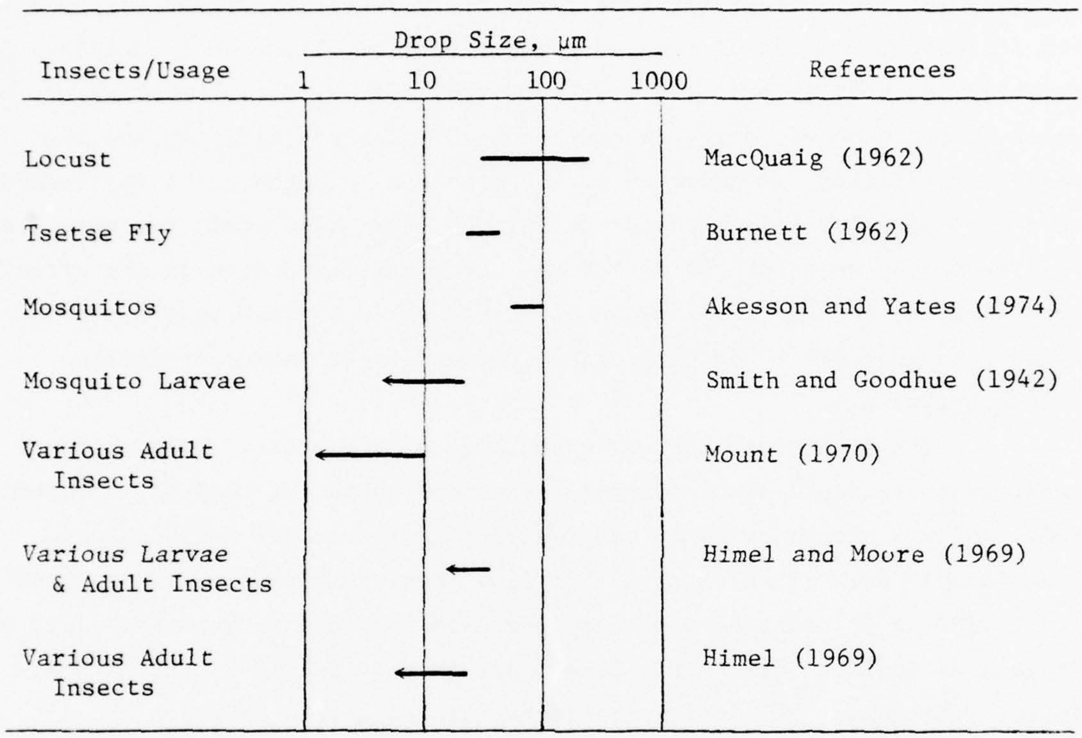

FIGURE 9. EFFECTIVE DROP SIZES AS REPORTED BY VARIOUS STUDIES

are sprayed without being diluted with water, the size of particles ranges from 50 to 100 μm in size. Actually, the smaller the size the more desirable for less wasteful distribution, coverage, and effectiveness of the chemical.

As drop size decreases the drop inertia becomes too small to settle on the ground rapidly. Thus, these drops can drift away before settling out. Extremely small droplets would remain suspended in the air for a prolonged period of time or even evaporate. These small droplets which do not readily settle out are defined as an aerosol. The extent to which these droplets drift depends upon the aircraft altitude and the weather conditions, in addition to the drop size. Although it may depend upon the degree of tolerance for drift, the upper size limit for aerosols may lie in the neighborhood of 100 μm. From the discussion on the effective drop size and on the minimization of drift, it is obvious that the drop size to be used has to be compromised between these two contradicting characteristics.

The drop sizes currently employed in the aerial application of pesticides are found to be primarily dependent upon the toxicity of chemicals, the area to be covered, and the period of chemical degradation. Akesson and Yates (1974) stated that fine sprays whose sizes range from 100 to 300 μm in diameter are currently used for most forest pesticides and large area applications. This size range is also used for agricultural insect pathogens. This small size range insures a good coverage and also rapid results due to large surface area for a given amount of material. Moderately toxic materials are, however, sprayed with particle sizes of about 300 to 500 μm. For highly toxic materials which require a maximum drift control, drops up to 1000 μm are used. However, drops larger than 1000 μm are not commonly used owing to their inability to provide uniform coverage and avoid waste.

Table 2 summarizes the average drop size currently used in agricultural aviation applications. The listed drop size can, however, be somewhat varied by the material density, wind velocity and altitude of the airplane. It is noted that many of the most effective drop sizes for various insects, as shown in Figure 9, and the sizes listed in Table 2

TABLE 2. RANGES OF THE AVERAGE DROP SIZE COMMONLY USED

Condition or Usage	Examples	Drop Size Range, μm
• Large Area Application • Low Application Rate • Low Toxicity • Rapid Degradation	Forest pesticide Agricultural insecticides Vector and other low toxicity material	100 - 300
• Moderately Toxic • Good Coverage Desired	Most moderately toxic agricultural chemicals	300 - 500
• Toxic • Good Coverage Not Essential	Restricted herbicide	500 - 800
• Highly Toxic • Small Area Application	Phenoxy acids or other highly toxic material	800 - 1000

cover the entire size range from the submicron size up to 1000 μm. Considering that most chemicals used for agricultural purposes are moderately toxic and that uniform coverage is generally a primary requirement for most applications, the drop size most commonly used seems to be in the range of 25 to 500 μm in diameter.

Application Rate

Like the drop size range, the application rate also varies very widely in usual agricultural aviation applications. In general, the application rate is found to depend upon the type of pesticides, the type of formulation, the type of aircraft, toxicity of chemicals, and even the drop size employed. The lower limit of application rate occurs when small amounts of low toxic substance is sprayed over a large area using a small drop size. A typical application rate for this so-called "ultra low volume" is on the order of 1 oz/acre. However, the application rate can be as high as 20 gal./acre, typically when very coarse drops are sprayed over a small area. The drop size dependence of the application rate is primarily due to the fact that a spray of small drops can cover a wide swath while coarse drops would settle in a very narrow swath width, thus requiring an increased application per unit coverage area. In order to incorporate the above application rates into the current program, information on the spraying rate is also required. It is found that an aerial spraying is done over a large area typically at a rate of about 10,000 acre/hr, while for the case in which a small area is covered using coarse sprays, the rate is about 30 acre/hr.

In conjunction with the drop size ranges shown in Table 2 the collected information on application rate has been summarized in Table 3. The flow rates as listed in the table have been obtained by multiplying the application rate by the spraying rate. It is interesting to note that while both application rate and coverage rate are widely varied, the calculated flow rate falls into a narrow range of 5 to 40 ℓpm with an average rate of 30 ℓpm or 450 gph.

TABLE 3. RANGES OF APPLICATION RATES COMMONLY USED

Application Rate, gal./acre	Spraying Rate, acre/hr	Calculated Flow Rate, gal./hr (ℓpm)	Typical Drop Size, μm
1/128	10,000	78 (5)	< 100
1	300	300 (20)	100 - 300
5	100	500 (33)	300 - 500
10	75	750 (50)	500 - 800
20	30	600 (40)	800 - 1000

Liquid Properties

As discussed previously, most pesticides have been found to be sprayed combined with carriers such as water or oil. Therefore, properties of the liquid chemicals and the application rate can vary widely depending upon the degree of dilution. Generalization of the liquid properties is further complicated by the fact that supplemental additives such as spreading agents, adhesives and emulsifiers are often added to the solution. Physical properties of some carrier liquid materials quoted by Butler, et al. (1969) are listed in Table 4. It can be noted that density of most carrier liquids ranges from 0.8 to about 1.25 g/cm^3. Surface tension is found to be between 20 to 30 dyne/cm. A wide range of viscosity, however, exists ranging from 0.3 to about 10,000 cp. With the two liquids having an extremely high viscosity excluded, the viscosity for a typical liquid would range from 0.3 to about 500 cp.

Although intrinsic properties of the original chemicals do not greatly affect the overall combined properties of the final solutions, vapor pressure of the material can be important especially in relation to its toxicity. For example, the vapor pressure of Malathion as listed in

TABLE 4. PROPERTIES OF SOME LIQUIDS USED IN AGRICULTURAL APPLICATIONS

Liquid	Density, g/cm^3	Surface Tension, dynes/cm	Viscosity, cp at 20 C	Vapor Pressure	
		(20 C)		mm Hg	at temp, C
Acetone	0.79	24	0.32	195	20
Methanol	0.8	22	0.6	100	20
Benzene	0.9	30	0.65	80	20
Water	1.0	72.8	1.0	18	20
Ethanol	0.79	22	1.2	47	20
Gasoline	0.68	--	0.35	--	--
Turpentine	0.867	--	1.49	3	20
Kerosene	0.82	25	2.5	7	30
Diesel Fuel	0.89	30	10	--	--
Ethylene Glycol	--	47	20	--	--
Cottonseed Oil	0.92	35.4	70	--	--
Lube Oil SAE10	0.9	36	100	--	--
Lube Oil SAE30	0.9	36	300	1	30
Castor Oil	0.97	39	1,000	--	--
Corn Syrup	--	78	10,000	--	--
Malathion (95 %)	1.23	32	45	4.0×10^{-5}	30
Lindane	--	--	--	9.4×10^{-6}	20
Parathion	1.35	--	--	4.0×10^{-5}	20
2,4-D	--	--	--	1.1×10^{-2}	25
Dursban (75 %)	0.97	--	--	1.87×10^{-5}	25
Naled (85 %)	1.965	--	--	--	--
Fenthion (93 %)	1.25	--	--	2.15×10^{-6}	20
Captan	1.73	--	--	1.0×10^{-5}	25

Table 4 is about 4×10^{-5} mm Hg at 20 C. 2,4-D, on the other hand, has a rather high vapor pressure of about 10^{-2} mm Hg (Butler, et al., 1969). Intrinsic material density of most chemicals is found to be approximately between 1.2 and 2 g/cm^3. Information on the intrinsic viscosity and surface tension of these materials, however, is not readily available.

In relation to the overall effective viscosity of a certain type of mixture, it should be mentioned that this type of formulation can have characteristics of a non-Newtonian fluid. Thus, viscosity of the mixture is no longer proportional to the rate of shear stress. Especially water-in-oil and some thickeners respond as non-Newtonian liquids, and the viscosity will decrease as the shear rates increase. For example, a mixture of 10 percent diesel fuel and 85 percent water is found to have a viscosity of about 700 cp at a rate of 1/50 second while the value decreases to about 15 cp at 1/4000 sec. In any case, the viscosity of this material appears to fall within the viscosity range shown in Table 4.

Summary

The results of literature surveys on the drop size, application rate and properties of liquid material revealed that the formulation type varies from one type of chemical to the next, and that they are used with a carrier. Water, oils and foams are commonly used as carriers. Also, a wide variety of ranges in each of the above categories is currently employed.

The drop sizes currently used range from 100 to 1000 μm in diameter. If the most effective drop size is included and highly toxic materials to be applied in a relatively small area are excluded, the most commonly used drop size can be further narrowed down to the range of 25 to 500 μm. The average flow rate of the material is found to be about 30 ℓpm, with the range of 5 to 50 ℓpm. Various formulations have been found to be applied combined with a large dose of carrier liquid. The ranges of the liquid properties of the materials are as follow:

Density:	0.8 - 1.25 g/cm^3
Viscosity:	0.3 - 500 centipoise
Surface Tension:	20 - 80 dyne/cm
Vapor Pressure:	1 - 200 mm Hg.

ASSESSMENT OF THE CURRENT STATE OF THE ART

Although a monodisperse spray can be defined mathematically as a spray consisting of drops of one size, such a spray in reality seldom exists and is nearly impossible to produce. Generally, a monodisperse spray is referred to a spray whose drops are very narrowly distributed. Thus, the definition, "nearly monodisperse" is a relative term since a size distribution of drops which is sufficiently narrow in one application may be considered not monodisperse in another. For that reason, the terms such as "nearly monodisperse" or "moderately monodisperse" are often used. In this case the choice of the exact criterion for this state is sometimes arbitrary. As already described, a monodisperse spray for this study is defined as a spray containing drops 95 percent of which are smaller than 1.2 times the average drop size and with 5 percent of the drops smaller than 0.8 times the average size.

It should be pointed out that even if there exist available techniques or devices for producing a spray which meets the monodispersity criterion, some additional problems might have to be considered. One is that uniform drops initially produced by such devices can coalesce quickly to create doublets or triplets. In general, such coagulations occur when there are a large number of drops occupying a small space. Air turbulence or other means, such as Brownian diffusion or unequal settling rates can also cause the primary drops to coalesce. If such coagulation takes place to a severe extent, monodispersity of the drops would quickly deteriorate. This problem can be eliminated or lessened by proper operation of the devices such as employing appropriate dispersion air around the spray. Another problem is that some of the droplets can have shapes different from sphericity causing estimations of monodispersity to be rather difficult. Therefore, it is sometimes necessary to tolerate a small portion of odd-shaped droplets in such a case.

Using the background information on the range of drop sizes, liquid properties and application rates that are currently employed in the agricultural aviation field, and by considering the principles of

operation for existing techniques for producing monodisperse sprays, it is possible to assess the probability of developing such techniques into an operational system appropriate for the use in agricultural aviation applications. This section follows this procedure and assesses the state of the art for each identified technique with respect to the requirements. The specific requirements considered in this program are monodispersity of the drop size distribution, range of the average drop size, and ability to cover the required range of application rates. Among the identified techniques, only those which produce a monodisperse or nearly monodisperse spray will be considered; these are: (1) periodic vibration of liquid jet or reservoir, (2) electrostatic atomization, (3) ultrasonic atomization, (4) spinning disk or top, and (5) vaporization-condensation.

Periodic Vibration of Liquid Jet or Reservoir

Sprays produced using periodic vibrations generally have excellent monodispersity whether the technique employs a piezoelectric crystal, a sound speaker, or some sort of mechanical means. Since each individual drop is produced one at a time by means of a periodic disturbance in this technique, the resulting drop size is not greatly dependent upon the liquid properties. Among the reported dispersity, Magarvey and Taylor (1956) found that only 0.2 to 1.5 percent of the drops produced using an earphone-like vibrator have sizes different than the rest. The converted standard deviation on a weight basis was then between 0.0008 to 0.0022 which is equivalent to a geometric standard deviation of 1.001 - 1.002. Berglund and Liu (1973) measured the geometric standard deviation of the fine sprays produced using a piezoelectric crystal to be about 1.01. This is also well within the criterion established for the present program. The droplets produced by Binek and Dohnalová (1967) using a whisker, as previously described, have a geometric standard deviation ranging from 1.005 to 1.08.

The size of droplet produced is given by the following formula which may be readily obtainable by the balance between the mass of droplets produced per unit time and the liquid flow rate. Therefore,

$$\frac{\pi}{6} D^3 f = \frac{\pi}{4} d_j^2 u , \qquad (5)$$

where D is the droplet size, u is the liquid velocity, d_j is the jet diameter, and f is the vibration frequency. From Equation (5), the droplet size becomes

$$D = 1.145 \left(\frac{d_j^2 u}{f}\right)^{1/3} . \qquad (6)$$

Hence, the diameter of drops that can be produced in practice depends only upon the flow rate and frequency of the pulse and is not dependent on liquid properties. Implicitly, this assumes that the liquid stream is integrated into one droplet upon each pulse. For this reason, a high amplitude may be necessary for a highly viscous liquid. Since the amplitude of pulse is easily varied with a standard pulse generator, this problem is an operating condition rather than design criterion and Equation (5) still remains valid for predicting the drop size.

If the volume of droplets is equal to the volume of the cylindrical jet per wavelength, λ, we have an expression for the frequency as

$$f = u/\lambda . \qquad (7)$$

For optimum operating conditions, Rayleigh's linear theory (1879) on the instability of a liquid jet is utilized. The optimum wavelength of vibration as a result of his theoretical study is given by

$$\lambda_{opt} = 9r_j , \qquad (8)$$

where λ_{opt} is the optimum wavelength of vibration and r_j is the jet radius. Equation (8) was derived for a nonviscous, incompressible, liquid jet sprayed into a vacuum. From the consideration of surface energy, Plateau (1873) derived

$$\lambda_{opt} = 2\pi \; r_j . \qquad (9)$$

Schneider and Hendricks (1964) experimentally determined that monodisperse sprays can be produced in the wavelength range of

$$7r_j < \lambda < 14r_j \ .$$

Berglund and Liu (1973) also found a similar range of wavelength that can produce uniform droplets as shown in Figure 10. Rajagopalan and Tien (1973) experimentally found that there is always a certain minimum threshold frequency required below which no uniform droplets were formed and above which uniform droplets were produced. For a high viscosity liquid, they found the threshold frequency to be

$$f_{th} = 0.7f_{opt} \ , \tag{10}$$

and for low viscosity liquid,

$$f_{th} = 0.4f_{opt} \ , \tag{11}$$

where f_{th} is the threshold frequency. They also found that amplitude of disturbance has very little effect on the production of monodisperse droplets. This can also be shown in Figure 10 in which uniform droplets can be generated over an amplitude of several orders of magnitude while the optimum wavelength range is very narrow.

Figure 11 summarizes the drop size range that could be covered by the periodic vibration technique showing that essentially a wide range of drop sizes has been already experimentally demonstrated. It is important to note in the figure that drop sizes smaller than about 50 μm can be best produced using an electrostrictive transducer such as piezoelectric crystal. A periodic acoustic signal produced with a sound-speaker type vibration is well suited for producing drops larger than 50 μm. Of course, these two distinctively separate ranges are due to the difference in the vibration frequency which in turn determines the drop size.

The flow rate obtained in the atomization using a periodic vibration of a liquid jet or a liquid reservoir is extremely low. For example, a combination of frequency, 700 kHz, and drop size, 10 μm, yields a flow rate of only 0.022 cc/min and a combination of 10 kHz and 200 μm results

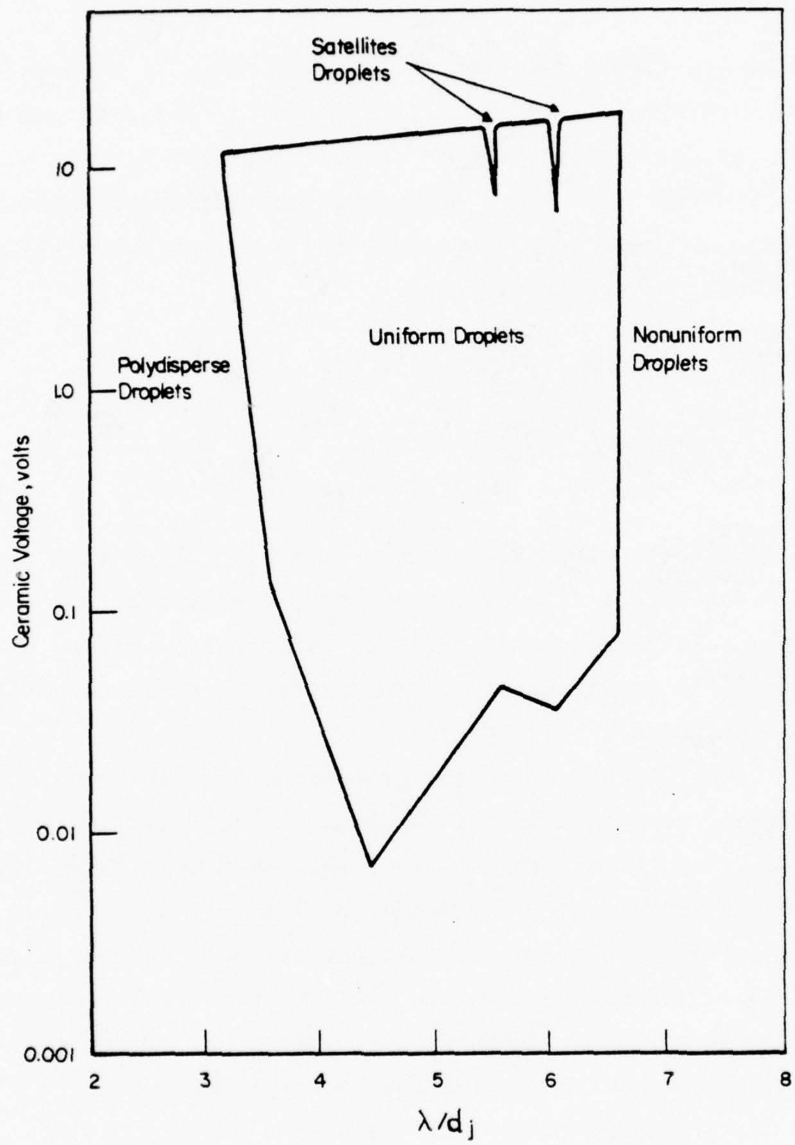

FIGURE 10. PERFORMANCE REGIMES FOR VIBRATING ORIFICE SPRAYER (Berglund and Liu, 1973)

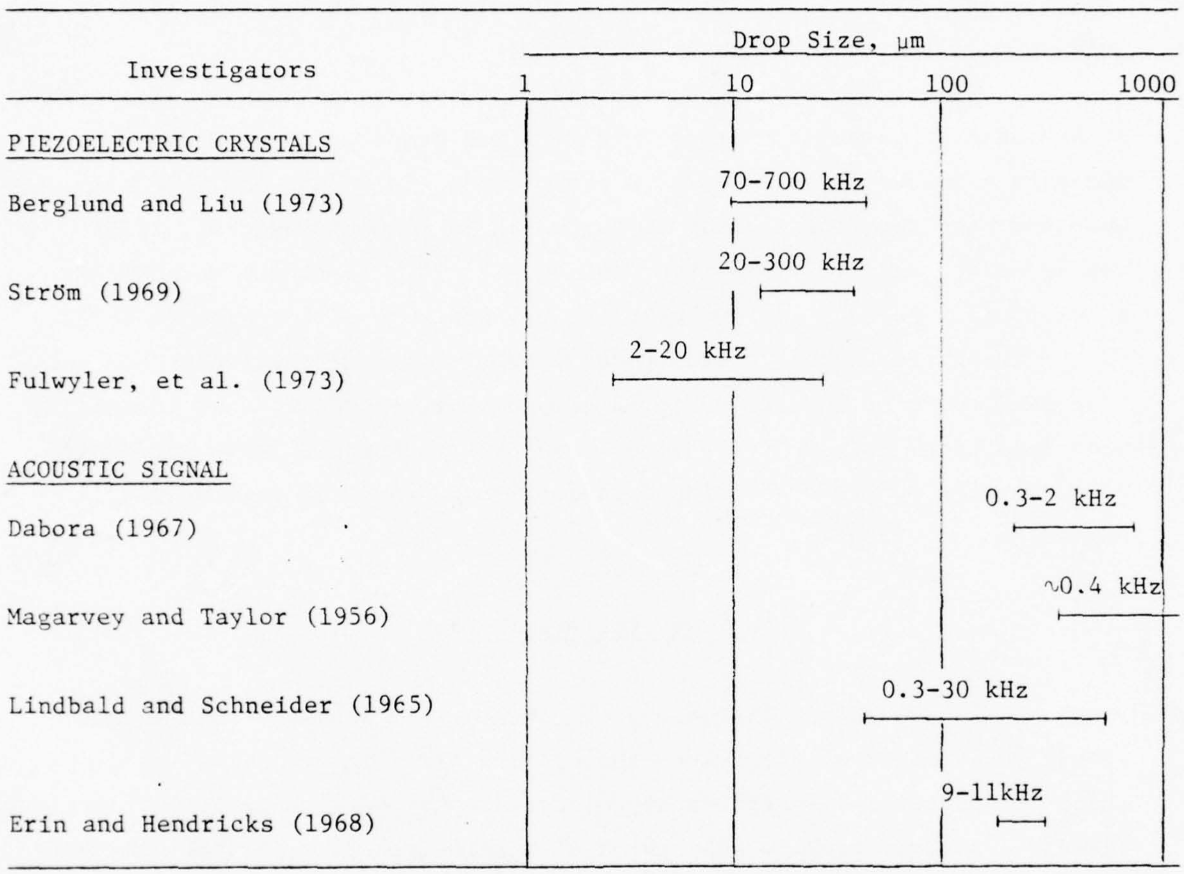

FIGURE 11. RANGE OF AVERAGE DROP SIZES COVERED BY SPRAYERS USING VARIOUS PERIODIC JET VIBRATION FREQUENCIES

in a flow rate of 2.5 cc/min. Since these flow rates are not sufficient to be used in a practical application, it is necessary to seek ways to increase the flow rate. One possibility will be to increase both the vibration frequency and the flow velocity, using the relation shown by Equation (5), while the wavelength of the signal is kept within the Raleigh's criterion as given in Equation (8).

Figure 12 shows the calculated flow rates against the drop size at elevated frequencies. It is seen that for drops of about 250 μm produced at a frequency of 100 kHz, a flow rate of 50 cc/min can be achieved. Compared with the flow rate of 30 ℓpm which is commonly used in aerial applications, this requires about 600 tubes. If a frequency of 1000 kHz is employed, the required number of tubes, however, will reduce to about 60. A design for such a system consisting of multiple tubes can be such that many tubes be mounted having a common vibrator rather than installing many individual units. It is also possible to design a large perforated plate mounted on a shallow liquid reservoir and then the reservoir wall or bottom can be vibrated.

Electrostatic Atomization

As previously discussed, electrostatic dispersion of a liquid involves a variety of processes, the applied electric potential, and liquid properties. Generalization of the droplet size range is not straightforward. Another problem associated with this technique is that most previous investigations have been concerned with the basic mechanisms for droplet formation rather than with the monodispersity of the droplets or the droplet size range. In general, the size of drops produced by electrostatic atomization depends on the applied voltage, surface tension of liquid, capillary tube diameter, flow rate, electrical properties of liquid such as dielectric constant and electrical conductivity. These effects can be discussed in terms of flow rate and applied voltage as well as in terms of industrial applications.

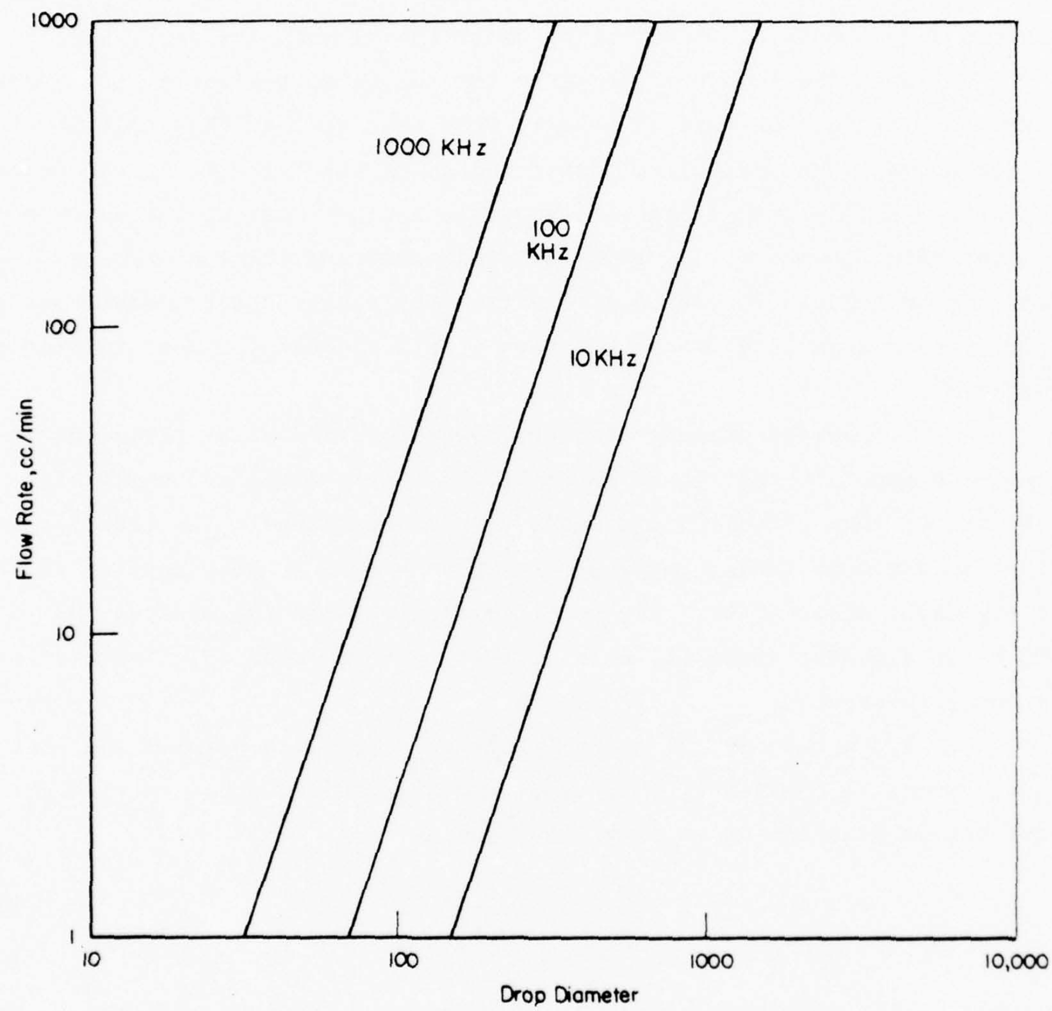

FIGURE 12. DESIGN FLOW RATE PLOTTED AGAINST DROP SIZE AT VARIOUS FREQUENCIES

The electrostatic atomization methods commonly used in the electrostatic painting industries uses the painting surface as one electrode, and involve a relatively high liquid flow rate with a high voltage. Flow rates up to about 1 gal./min. can be sprayed using voltages of up to 100 kv. The liquid is generally pressurized and fed into the atomizer. Droplet size distribution of the sprays produced under these conditions are rather broadly dispersed, although no quantitative experimental data are available.

When the liquid is fed into the nozzle at the atmospheric pressure, the liquid flow rate is usually very much smaller than that discussed above. The typical voltage required in this case is on the order of 10 kv. This process, however, produces a wide range of the average droplet size between 0.1 to 1000 μm in diameter and their dispersity is known to be relatively narrow as confirmed by a high order Tyndall Spectra. This type of atomizing method has been widely adopted for most laboratory research.

In microelectronic circuit industries, a similar technique is used. In general, the liquid materials, or often times molten metals, are sprayed onto circuit board under vacuum conditions. The liquid flow rate is extremely small, ranging only up to 4 cm^3/hr. The applied voltage is typically about 10 kv. The reported droplet size ranges from 300 to 600 μm in diameter (Bollini, et al., 1975) with no available information on the monodispersity.

For a theoretical analysis, Zeleny (1914) calculated the electrostatic pressure exerted by a liquid. For a spherical drop, he gave an equilibrium equation of various pressures as

$$\frac{2\sigma}{r_p} = P + \frac{V^2}{8\pi r_p^2} \quad , \tag{12}$$

where V is the applied voltage, r_p is the droplet radius, σ is the surface tension of the droplet, and P is the excess pressure inside the droplet. As the electric voltage increases, an equilibrium no longer exists. Although calculation of the exact number of electrical charges in terms of the applied voltage is complicated due to the nonspherical shape of the

droplet at the end of the tip, Zeleny said instability takes place when the following condition is met: $V^2 = cr_p\sigma$; where c is a constant depending on the shape of the droplet. Thus, if the electric voltage becomes excessive, the liquid surface starts disintegrating.

Later, Vonnegut and Neubauer (1952) predicted the following particle size by considering the balance between the electrical energy and the surface energy, similar to Equation (12):

$$D = 2\left(\frac{9kQ^2\sigma}{4\pi\ q^2}\right)^{1/3} , \tag{13}$$

where q is the total number of electrical charges, Q is the volume of the liquid reservoir, and k is a constant. The number of particles produced, n, was given by

$$n = \frac{q^2}{3kV\sigma} . \tag{14}$$

Although Equations (13) and (14) are one step above Zeleny's analysis, they still contain an adjusting constant, k. Further, these equations have not been experimentally verified.

Due to relatively few quantitative studies and lack of comprehensive understanding of the basic principle, it is rather difficult at present to assess the flow rate that can be achieved. For a reasonably monodisperse spray, the flow rate should be maintained at an extremely small rate and a scale-up for such devices can pose some difficulties. Another drawback of this technique is that both the operations and characteristics of the produced sprays are significantly dependent on the electrical property of the liquid. As already discussed, some organic materials such as benzene which is currently used as a carrier for aerial application, cannot be dispersed into drops. No further consideration will be given to this technique for these reasons.

Ultrasonic Atomization

Sprays produced based on the principle of ultrasonic atomization technique seem to attain a relatively narrow dispersity, although it might be less satisfactory than that provided by the vibrating tube method. For example, Lang (1962) stated that 90 percent of the droplets produced were smaller than twice the average size. Compared to the present criterion that the size of 95 percent of the drops should be smaller than 1.2 times the average size, the quality of sprays quoted by Lang is not quite satisfactory. One way to measure the dispersity of droplet size is to plot the cumulative percent against the drop size. Figure 13 shows the size distributions of the sprays produced by Doyle, et al. (1967), using the ultrasonic atomization technique. Based on the original size distributions, the geometric standard deviations for these sprays have been calculated and included in the figure. The following equation has been used for this calculation:

$$\sigma_g = \frac{D_{84\%}}{D_{50\%}} = \frac{D_{50\%}}{D_{16\%}} = \left(\frac{D_{84\%}}{D_{16\%}}\right)^{1/2} \tag{15}$$

where

σ_g = the geometric standard deviation

$D_{i\%}$ = the drop size below which there are i percent of the total drops on a weight basis.

For a theoretical prediction for the droplet size, Peskin and Raco (1963) found that the acoustic atomization process can be governed by several nondimensional parameters. Figure 14 gives the droplet size in terms of transducer amplitude a, frequency ω_o, liquid film thickness h, surface tension σ, and fluid density ρ. The drop size is seen to be a function of frequency and the film thickness. For high frequencies, the drop size becomes a function of film thickness as shown in Figure 15. For large film thickness, their analytical result reduces to

$$D = (4\pi^3\sigma/\rho\omega_o^2)^{1/3} \quad . \tag{16}$$

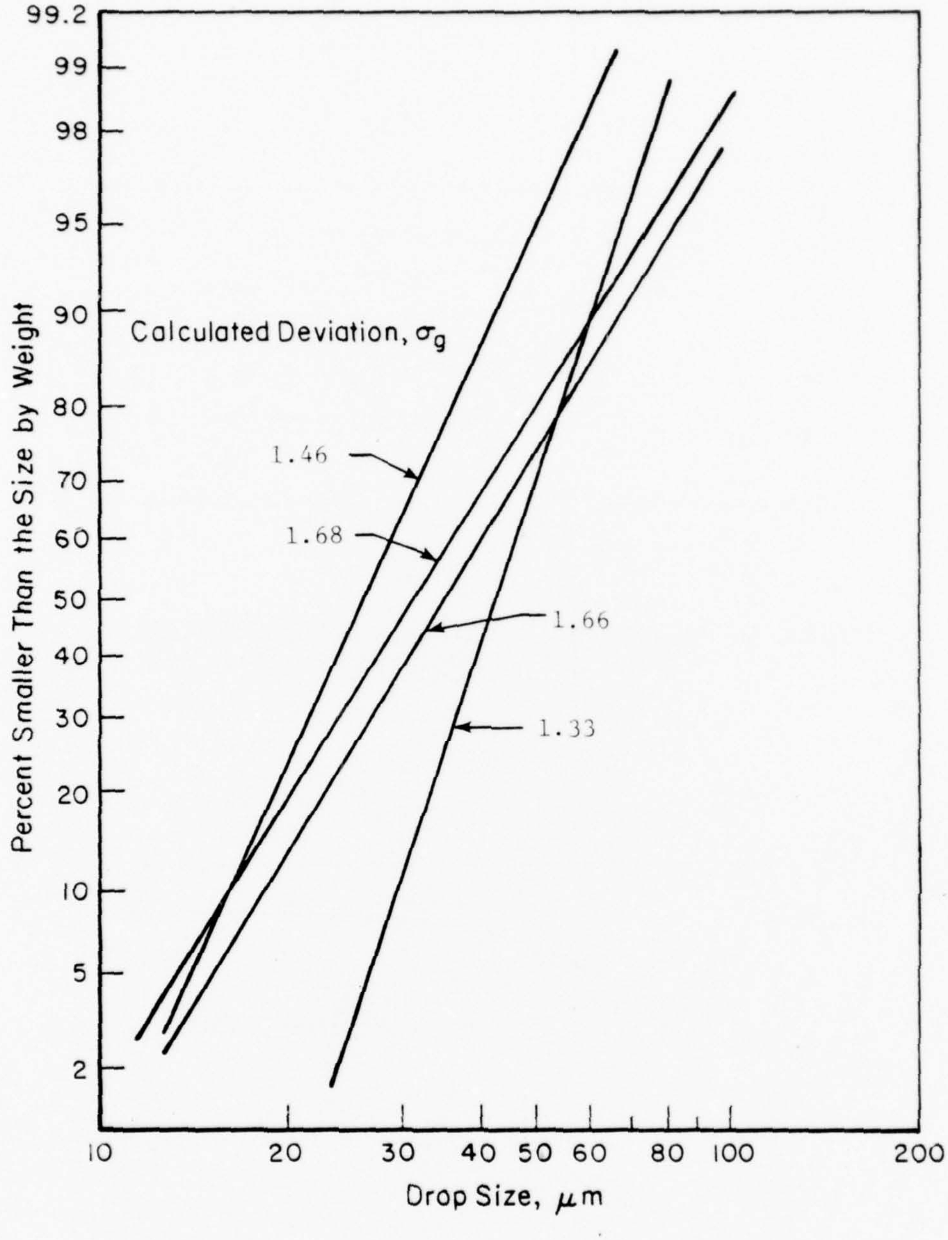

FIGURE 13. SIZE DISTRIBUTION OF THE SPRAYS PRODUCED BY ULTRASONIC ATOMIZATION TECHNIQUE

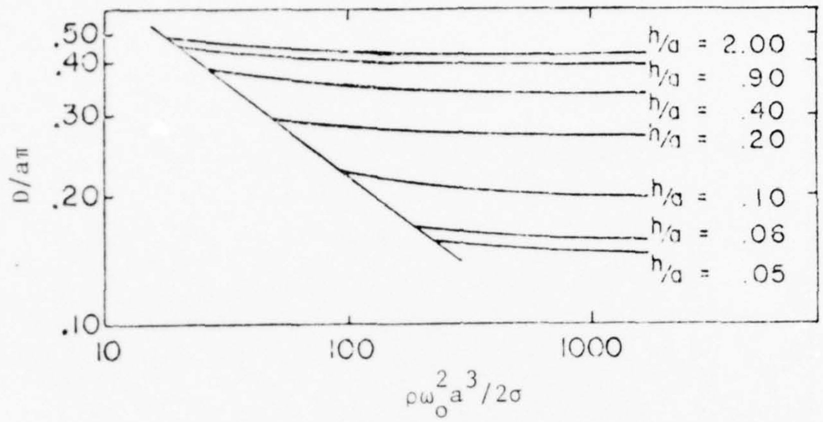

FIGURE 14. RELATIONSHIP BETWEEN THE NONDIMENSIONAL GROUPS IN ULTRASONIC ATOMIZATION (Peskin and Raco, 1963)

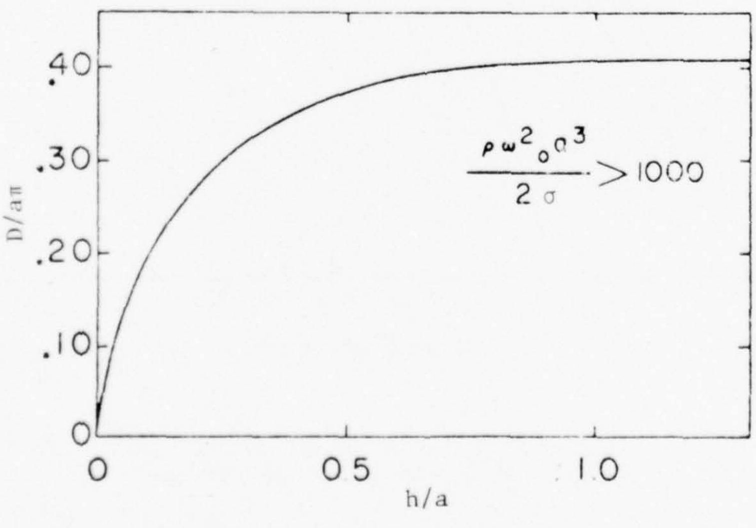

FIGURE 15. DROP SIZE AS A FUNCTION OF FILM THICKNESS (Peskin and Raco, 1963)

Although the relationship given in Figures 14 and 15 has not been experimentally proven, Equation (16) has been confirmed by many experimental studies such as Lang (1962) and Crawford (1955). For a large value of $\rho\omega_0^2 a^3/2\sigma$, Equation (16) is further approximated by

$$D = 0.42\,\pi\, a \ . \qquad (17)$$

A wide range of the average size has been experimentally covered using the ultrasonic atomization technique. Figure 16 summarizes the drop size range covered by various investigators. The operating frequency used in the studies ranged from 10 to 2000 kHz. It can be concluded that the ultrasonic atomization can cover the low size range of the drops currently used in agricultural aviation applications.

Ultrasonic atomizers can, however, handle a relatively small amount of liquid primarily due to the low amplitude of oscillations that ultrasonic transducers generate. A typical value for the maximum liquid flow rate for an ultrasonic atomizer currently in use is about 1 gph. The corresponding frequency in this type of atomizer is typically 40 kHz. One way to increase the flow rate is to combine the principle of ultrasonic atomization with that for the whistle type atomization as employed for some industrial purposes. Thus, the amplitude of signals produced initially by ultrasonic transducers is further amplified due to the resonant effects created by the hollow space of the horn shape. While this design allows the capacity to be increased substantially, it will restrict the operating frequency of the transducer to one value. Since the drop size produced using ultrasonic atomizers is dependent upon the transducer frequency as shown in Equation (16), this arrangement is restricted to producing one drop size. Obviously, a series of different sets are necessary to cover the required size range.

Another way to increase the flow rate is again to install many atomizers in parallel. It is, however, expected that there would be mutual interference effects of oscillations produced by these transducers. Since this interference can produce an unwanted spray of polydisperse drops, it might be necessary to install a transducer in a separate chamber.

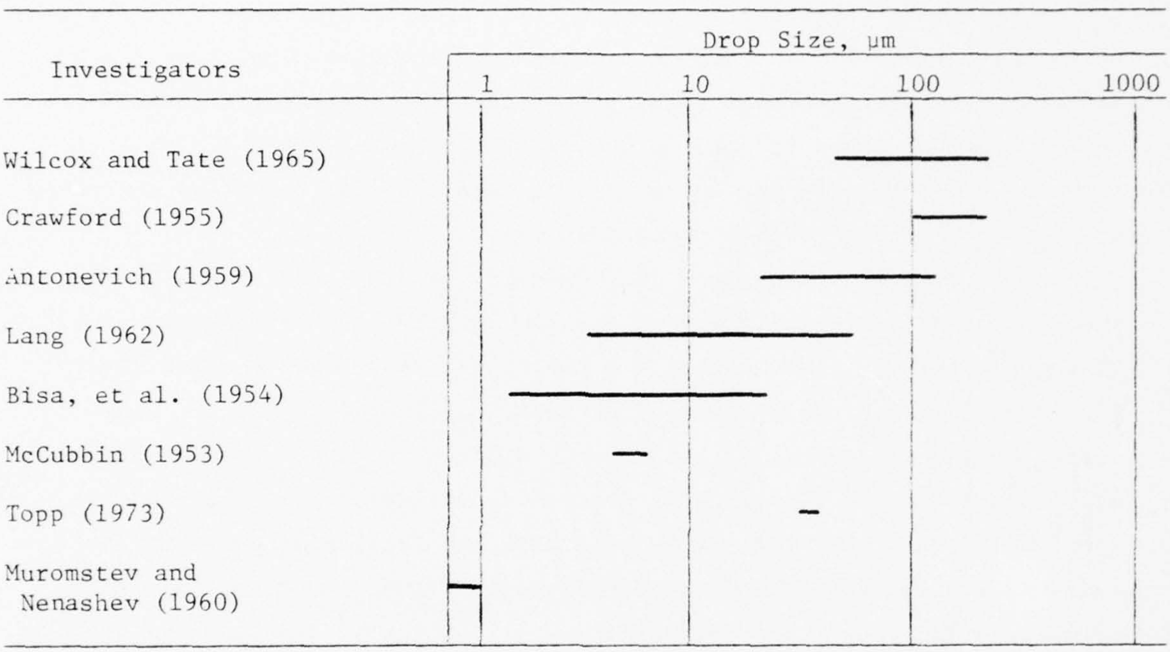

FIGURE 16. RANGE OF DROP SIZES COVERED BY VARIOUS STUDIES EMPLOYING AN ULTRASONIC ATOMIZER

Spinning Disk

Unlike conventional atomizers such as pressure type nozzles or two fluid atomizers which invariably produce sprays of very heterogeneous size distribution, the spinning disk is capable of producing sprays of very uniform droplet size. The geometric standard deviation of the sprays reported by Lippmann and Albert (1967) ranged from 1.05 to 1.72. The standard deviation of the aerosols produced by Philipson (1973) measured to be about 4 percent of the mean. May (1949) found that the water spray generated by the spinning disk method has a standard deviation of 5 percent of mean size. Further, the 90 percent band width encompassed the size range from 0.94 to 1.06 times the mean. The minimum drop size was found to be 0.91 times the mean size. A typical size distribution of the sprays as measured by May is shown in Figure 17. It should be noted, however, that the satellite droplets are not included in the figure.

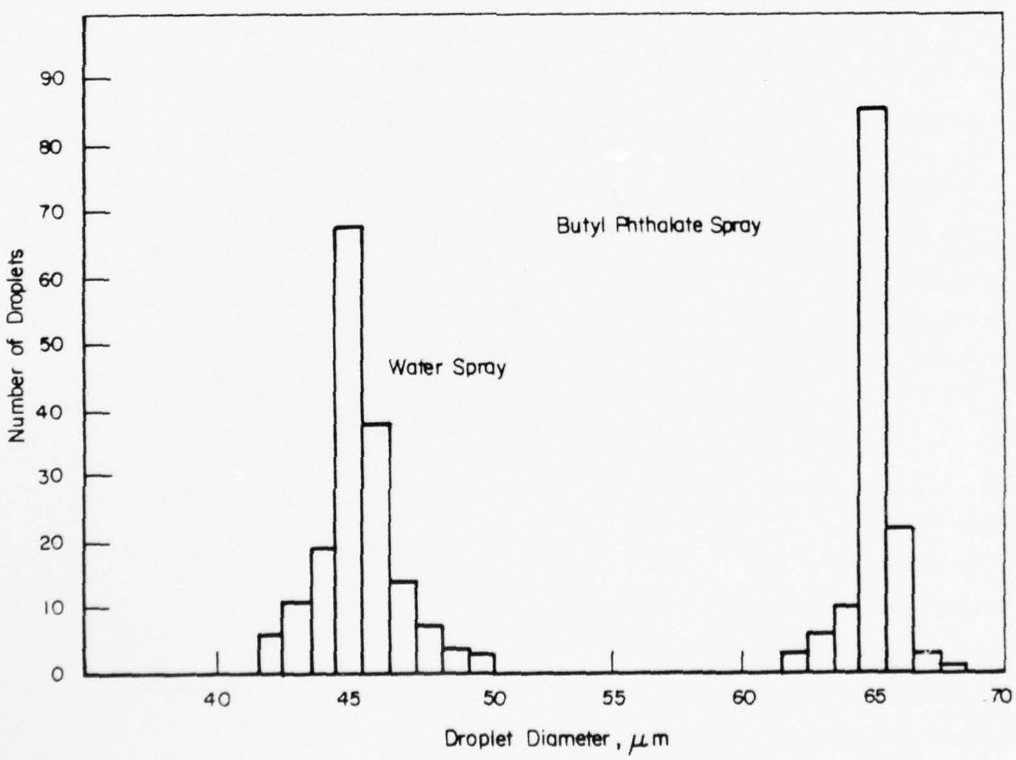

FIGURE 17. SIZE DISTRIBUTION OF A SPRAY PRODUCED BY A SPINNING DISK ATOMIZER (May, 1949)

For the size range and the operating conditions of the spinning disk method, a well-established correlation exists. Assuming the disk is uniformly wetted, the liquid flows as a thin film from the center of the disk to the edge and accumulates until the centrifugal force of the liquid becomes equal to the attraction force due to surface tension.

The centrifugal force, F, is

$$F = m \frac{v^2}{R} = mR\Omega^2 \quad , \tag{18}$$

where

m = the mass of a droplet $(= \frac{\pi}{6} \rho D^3)$

R = the disk radius

Ω = the angular velocity of the disk.

The attraction force is proportional to the surface tension. Therefore,

$$F = k\sigma D \quad , \tag{19}$$

where k is a constant to be experimentally determined. From Equations (18) and (19), the drop size can be written as

$$D = \frac{k}{\Omega} \sqrt{\sigma / 2R\rho} \quad . \tag{20}$$

Various investigators determined experimentally the proportionality constant appearing in Equation (20). For example, Walton and Prewett (1949) found that uniformly sized droplets can be successfully produced in the range of

$$2.67 < \Omega D \left(\frac{2R\rho}{\sigma}\right)^{1/2} < 4.44 \quad ,$$

and Philipson (1972) gave

$$2.64 < \Omega D \left(\frac{2R\rho}{\sigma}\right)^{1/2} < 3.06 \quad .$$

Equation (20) indicates that the droplet size can be varied by using a different disk size or by altering the rotational speed. For obvious convenience, the latter method is commonly used to vary the droplet size.

Results from several of the available experimental studies are summarized in Table 5. Among these experimental investigations, Walton and Prewett experimentally cover the widest range of droplet diameters. The average droplet diameters in their experiments ranged from 180 to 3000 μm

TABLE 5. SUMMARY OF VARIOUS EXPERIMENTAL STUDIES FOR SPINNING DISK TECHNIQUE

	Walton and Prewett (1949)	Lippmann and Albert (1967)	Philipson (1973)	May (1949)	May (1966)	Hillenbrand (1978)
Type	Disk and top	Disk	Disk	Top	Top	Top
Droplet Size, μm	180 - 3000	1 - 10	3 - 10	∿50	10 - 200	0.5 - 10
Liquid Flow Rate, cm^3/min	up to 180	18	0.5 - 4			1 - 1.5
Liquid Used	Mercury, water, dibutyl phthalate, glycerine, paraffin, and others	Iron oxide	0.4% polystyrene in xylene with mesitylene	Oil, water		Salt solution, polystyrene in xylal
Rotational Speed, rpm	600 - 6000	21000 - 60000	25000 - 75000	up to 2.4×10^4	1.5×10^5	
Diameter of Disk or Top, cm	2 - 8	2.7	2	2.6	2.5	

with the spinning disk diameter ranging from 2 to 8 cm. The rotational speed was varied between 600 to 4000 rpm. The ranges of the liquid properties tested were: viscosity, from 0.01 to 15 poise; density, from 0.9 to 13.6 g/cm^3; and surface tension, 20 to 450 dyne/cm. He also studied experimentally the performance of a spinning top of 3 cm in diameter. A droplet size range of 10 to 100 μm was produced. May (1949) *studied the spinning* top onto which a pressurized liquid was fed. The liquids he adopted were water and oil. The mean droplet size as a function of the air pressure for his atomizer is shown in Figure 18. The size of the top was about 1 inch in diameter and the rotational speed was approximately 4000 rps.

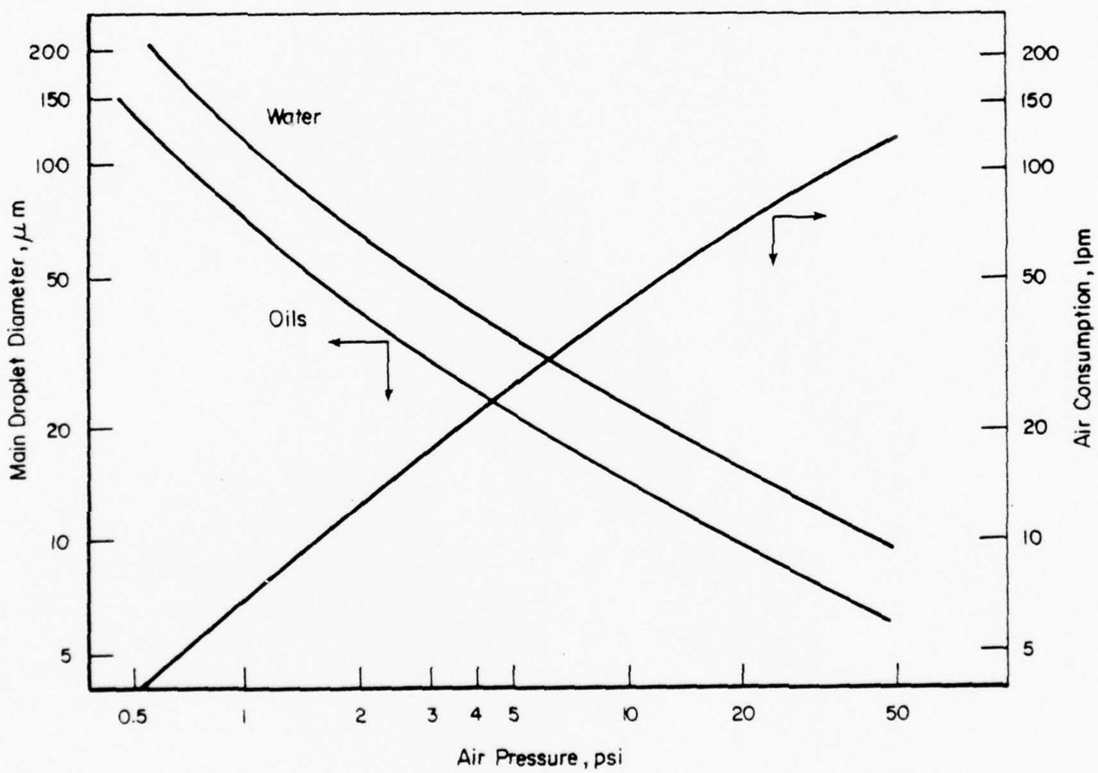

FIGURE 18. PERFORMANCE CURVES FOR SPINNING TOP ATOMIZER (May, 1949)

The liquid flow rate onto the disk should be kept relatively low. When an excessive amount of liquid is attempted to be fed, the fluid inertia force becomes important, causing the liquid leaving the edge in the form of a thin sheet. This sheet of liquid later breaks up into various sized droplets, thus, resulting in the unwanted wide size distribution. Assuming that flow rate can be increased proportional to the square of the radius, a disk diameter of 50 inches would be necessary to meet the required flow rate of about 30 ℓpm. Since no systematic studies have been made for the actual performance of such a large scale spinning disk atomizer, various operating conditions and quality of the produced spray have to be evaluated. Another way to increase the capacity is to design a system of stacked spinners having a relatively large diameter. As previously discussed, one problem which seems to occur most often with spinning disks is the production of unwanted satellite droplets. Although arrangement of a secondary flow can eliminate these droplets to a certain extent, it might be difficult to design such a secondary flow that could operate properly under the variable wind conditions caused by the aircraft speed.

Vaporization-Condensation Technique

If well controlled on a small scale, the vaporization-condensation technique provides a moderately monodisperse spray whose geometric standard deviation ranges from about 1.2 to 1.8 (Lee, 1978). However, it is expected that the drop size distribution of the sprays produced by this type of technique would strongly depend upon the chemical composition of the liquid. Therefore, the above estimations might be different from liquid to liquid.

Theoretically, the mean size of the droplet produced by the condensation method is primarily determined by the condensation rate which, in turn, is controlled by the vapor velocity and the liquid-air ratio. When the vapor jet emerges into ambient air, a large amount of air is drawn into the jet. At the same time, turbulence causes the vapor to be mixed rapidly with the air. Thus, the mixing zone of the vapor and air is formed

where the vapor condenses on nuclei which proceed to grow into droplets. As the distance from the nozzle increases, the droplets encounter more air and the vapor pressure decreases until the growth rate of the droplets is negligible. Theoretical prediction of the drop size has already been given by Equation (1). Since the sprays produced by this technique are based on condensation of material on nuclei, the size of the drop is rather difficult to control. In general, the number of nuclei, vapor temperature and pressure, and flow rates of vapor and admixed air must be carefully controlled. In addition, the resulting spray drop sizes generally are less than 1 μm. For these reasons, no further consideration will be given to this technique.

COMPARISON OF VARIOUS EXISTING TECHNIQUES

Based on the information and discussions from the three previous sections, the techniques which could be further developed into the unit for agricultural aviation application are now to be rated. Table 6 summarizes the advantages and limitations of the techniques with respect to their ability to produce a monodisperse spray, to cover the required range of drop size, to accommodate various liquid properties, and to achieve sufficient flow rates. In order to compare these techniques more comprehensively, the requirements for the spraying nozzle that is to be developed are listed in Table 7. Since not all the requirements are of equal importance, weighting factors or priority levels have been assigned to each requirement with the maximum value of 3 points being given to the most important requirement. It should be noted that the importance levels shown in the table are those which are assigned for the purpose of the current development program and drop size distribution parameters such as monodispersity, average drop size and flow rate are the factors which have been chosen for comparing atomization techniques. Some of the requirements discussed previously have been omitted since they are not considered important for the present evaluation purpose.

Table 7 is now applied to the candidate techniques. For this purpose, Table 8 has been prepared using the current state of the art of each technique using A, B, and C. Thus, A indicates the technique already capable of achieving the requirement, while C indicates that the item should be further extended for the final version of nozzles. Then, each of the levels has been multiplied by the weighting point. This product is shown in parentheses. For this purpose, A has been given 3 points, B 2 points, and C 1 point. Finally, these points have been summed for each technique.

Depending upon the priority levels of each requirement, the results shown in Table 8 can be altered somewhat. However, it is interesting to note that periodic dispersion of liquid jet and spinning disk have shown about the same probability to be extended to the prototype design with ultrasonic atomization technique following closely. Electrostatic atomization and vaporization-condensation technique are, however, found not to be adequate for further consideration.

TABLE 6. COMPARISON OF VARIOUS SPRAYING TECHNIQUES

Requirements: Item	Requirements: Level	Periodic Vibration of Liquid Jet or Reservoir	Electrostatic Atomization	Ultrasonic Atomization	Spinning Disk Method	Vaporization-Condensation
Monodispersity of Sprays	Nearly monodisperse	Excellent		Good	Good; except producing satellite droplets	Good
Range of Average Drop Size, μm	25 - 500	3 - 1000	300 - 600	1 - 200	10 - 200	Aerosol range
Application Rate, ℓpm	5 - 50 (avg = 30)	Current flow rates extremely low; multiple units required	Very low	Relatively low flow rate; could be scaled up if combined with the whistle type	Relatively low; stacked disks required	up to 5 ℓpm
Liquid Properties:						
Density, g/cc	0.8 - 1.25	Not greatly dependent upon liquid properties	Strongly dependent upon electrical conductivity and dielectric constant; some organic liquids cannot be dispersed	Dependent on density and surface tension	Not strongly dependent upon viscosity; within current range of density	*Strongly dependent* on chemical properties
Viscosity, cp	0.3 - 500					
Surface Tension, dyne/cm	20 - 80					

TABLE 7. LIST OF REQUIREMENTS FOR SPRAYING NOZZLES AND THEIR PRIORITY LEVEL

Requirements	Weighting Point*
Capability of achieving a good monodispersity of sprayed drops	3
Ability to produce the required range of average drop size	2
Probability of extending the liquid application rate	2
Ability to accommodate the current range of liquid properties	2

* Key: 3 -- high importance
2 -- medium importance
1 -- low importance

Weighting point may or may not coincide with the intrinsic requirements for spraying nozzles.

TABLE 8. EVALUATION OF VARIOUS SPRAYING TECHNIQUES

Requirement (Weighting Points)	Periodic Vibration of Liquid	Electrostatic Atomization	Ultrasonic Atomization	Spinning Disk Method	Vaporization-Condensation
Monodispersity (3)	A*(9)	B (6)	B (6)	B (6)	B (6)
Range of Drop Size (2)	A (6)	B (4)	B (4)	A (6)	C (2)
Application Rate (2)	C (2)	C (2)	B (4)	B (4)	A (6)
Range of Liquid Properties (2)	A (6)	C (2)	A (6)	A (6)	C (2)
TOTALS	23	14	20	22	16

* Key: A -- 3 points; B -- 2 points; C -- 1 point.

NEW CANDIDATE TECHNIQUES

As a first step to generating a new means for producing a monodisperse spray, various possible approaches were studied. As reported in previous sections, there are many spraying principles and techniques which have been used in areas of paint spraying, mass spectroscopy, combustion application and basic spray and aerosol research. The most promising techniques were identified to be those based on periodic vibration of liquid jet, spinning disk or top, ultrasonic atomization and electrostatic atomization. These techniques were found to be very effective and appeared promising for refinement, modification and development into forms suitable for agricultural aviation purposes in terms of the range of average drop size, monodispersity and ability to operate over a range of liquid properties. However, since major emphasis of the second phase of the present program was to be given to untried concepts rather than refinement of the above existing principles, it was decided that these techniques were not to be pursued any further under this study. Therefore, some additional techniques or principles that had not been investigated in laboratory studies were first generated. Among the generated ideas which emerged as a result of this pursuit, pertinent ones are briefly discussed below. As will be stated later, three of the following ideas were further analyzed for conceptual designs:

(1) Centrifuge type chamber. Polydisperse spray produced by a conventional atomizer can be passed through a centrifuge type chamber such that large drops leave the chamber exit from the outer part while small drops leave from the center. If only those drops from an intermediate annular section are allowed to leave the exit and the remaining excessively large and small drops are recirculated, a spray of uniform drops would result.

(2) Atomization by two opposing air-liquid jets. By operating two twin fluid nozzles placed in opposition, liquid drops are allowed to experience a sudden accelerated or decelerated flow as they pass through shock waves set up in a tuned interspace.

Since acceleration of the droplets depends on their size, large drops would go through more stages of breakup than small droplets. Based on this principle, the droplets leaving radially from the two opposed nozzles become relatively uniform in size.

(3) Spinning disk coupled with an ultrasonic field. In order to overcome the intrinsic problem of low capacity associated with a spinning disk, cup, cone or similar shape, it was proposed that a spinning disk be operated at a high flow rate and then an ultrasonic field be imposed on the fluid sheet to convert the fluid sheet into droplets of uniform size.

(4) Rocket nozzle chamber. A rocket shaped combustion chamber has natural spinning acoustic modes. Although equivalent modes can be generated in small chambers of a similar shape, the frequency in that case would become very high. One alternative way is to make use of the flow itself to chop liquid jets as they emerge into the chamber. A modified fluidic device could be employed in place of a combustion process to drive such a system.

(5) Frozen particles. Another somewhat unusual but interesting idea that came up during the study is the possibility of converting the liquid material into the solid form which is more convenient for producing uniform particles. By initially freezing the liquid material of interest into the form of fine solid particles and then separating those solid particles into a narrow size range using an appropriate method, a spray of uniform sized frozen particles may be obtained.

Other ideas included a rotating brush, rotating wheels, atomization using a vortex flow and periodic vibration using sawtooth wave.

As revealed in the first phase of the program, one of the most important requirements for agricultural spray nozzles is the ability to produce a monodisperse spray. Preferably the produced spray would be such that only 5 percent by weight of the drops are larger than a maximum size and only 5 percent smaller than a minimum size, where the maximum and minimum are defined respectively as 1.2 and 0.80 times the average diameter. Secondly, the nozzle should produce sprays over the size range currently

employed for aerial applications. This range was found to be between 25 and 500 μm. Also, the nozzle should perform satisfactorily over the range of liquid properties currently used in agricultural applications. Ranges of the liquid properties are: density, from 0.8 to 1.25 g/cm^3; viscosity, from 0.3 to 500 centipoise; and surface tension, from 20 to 80 dyne/cm. Finally, the designed nozzle should be capable of covering the range of liquid flow rates, 5 to 50 ℓpm (80 to 800 gph) as discussed in a previous section.

The priority level for each of these requirements was already discussed.

Considering the above performance requirements, the first three of the generated ideas were pursued further. Conceptual designs using each of these principles are described subsequently.

Centrifuge Type Chamber

In the presence of centrifugal force, drops of different sizes move to the radial direction according to their size. Due to the dependence of the centrifugal force on the drop mass, large drops tend to move rapidly in the radial direction compared to small drops. Thus, if a polydisperse spray is subject to a flow having a swirling motion, it is possible to distribute the drops in different radial positions as a function of its size. While numerous devices such as centrifuges and cyclones have been developed using a similar principle for removing particulates or measuring the size distribution of a spray, this technique has not been used for producing a monodisperse spray.

If the excessively large and small drops among the drops distributed at a cross section can be removed, a spray of uniformly sized drops can be obtained. This section describes a conceptual design for such a nozzle.

Background

An initially polydisperse spray consisting of large and fine drops is introduced into a section near the axis in a tube in which a swirling flow is created by a rotor, as illustrated in Figure 19. Swirls can also be created by introducing the clean air radially. Thus, large drops are forced to the periphery of the tube while fine drops which are relatively little affected by the centrifugal force remain more or less in the center. By allowing the drops from an intermediate annular section to leave the exit and the remaining excessively large and small drops to be recirculated, a spray of uniform drops would result.

Swirling flows are a very complex phenomenon and it is rather difficult to perform an exact calculation of drop trajectories in such a flow. However, if some simplifying assumptions are made, as in the case of cyclones (Fuchs, 1964), it is possible to derive an analytic expression which can serve as a basis for the conceptual design for producing a monodisperse spray.

The motion of a drop in a swirling flow is subject to the following centrifugal force:

$$f = m \frac{v^2}{r} = \frac{\pi}{6} \rho\, d^3 \frac{v^2}{r} \qquad (21)$$

where

f = centrifugal force in the radial direction

m = mass of the drop

v = tangential velocity of the swirling flow

r = radial position of the drop

ρ = drop density

d = drop diameter.

The spray drop under this force then tends to move radially at such a velocity that the resistance due to the drag force becomes equal to this centrifugal force. According to the Stokes law, the resistance of a drop is expressed as follows:

$$f = 3\pi\mu d u_r \qquad (22)$$

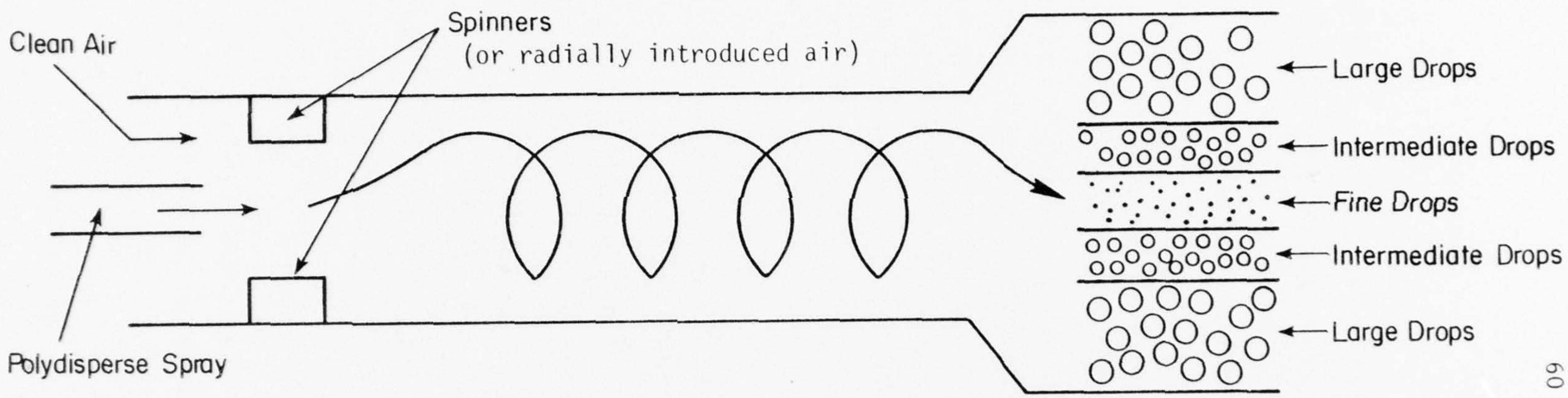

FIGURE 19. SCHEMATIC DIAGRAM SHOWING THE CLASSIFICATION PRINCIPLE OF DROPS USING A SWIRLING FLOW

where

μ = gas viscosity

u_r = radial velocity of the drop (= dr/dt)

t = time.

For a tengential velocity distribution of a swirling flow in a tube, the following simple expression, given previously by Shepherd and Lapple (1939) is used here:

$$v = ku_o \sqrt{R/r} \qquad (23)$$

where

k = proportionality constant

u_o = incoming flow velocity

R = tube radius.

Balancing the forces given by Equations (21) and (22), after substituting Equation (23) into Equation (21) we have the following differential equation:

$$dt = \frac{18\,\mu\, r^2\, dr}{k^2 d^2\, \rho\, u_o^2\, R} \; .$$

Subsequently, we integrate the above equation with an initial condition of $r = 0$ at $t = 0$ and obtain

$$t = \frac{6\,\mu\, r^3}{k^2 d^2 \rho u_o^2 R} \; . \qquad (24)$$

If the drop is swirled S times within the air flow (schematically shown in Figure 20) during the period of time, the total travel distance can be approximately assumed to be πrS. It should be noticed that half of r was used to calculate the distance. The average tangential velocity of the drop is estimated to be $v(r/2)$ in a similar fashion. Therefore we have

$$t = \frac{\pi rS}{v(r/2)} = \frac{\pi\, rS\sqrt{r}}{\sqrt{2}ku_o\sqrt{R}} \qquad (25)$$

where S is the number of swirls.

Eliminating t from Equations (24) and (25) we have an expression for drop size:

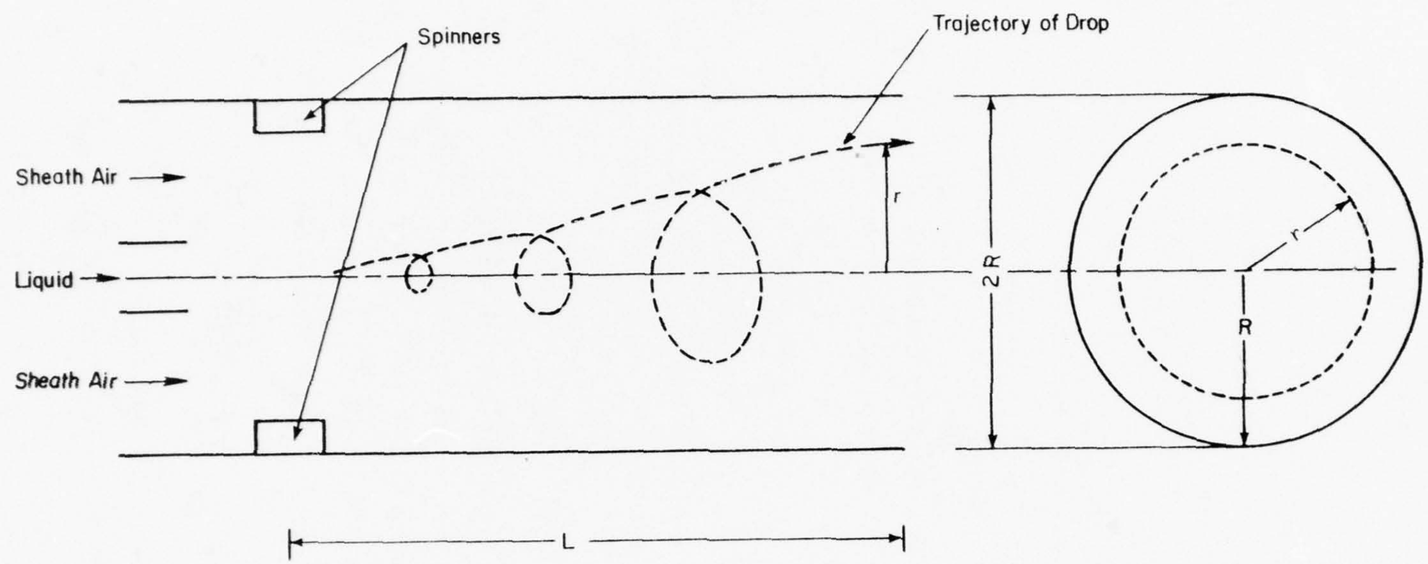

FIGURE 20. SCHEMATIC DIAGRAM SHOWING TRAJECTORY OF DROP

$$d = 1.643 \sqrt{\frac{\mu r^{3/2}}{kS\rho u_o \sqrt{R}}} \tag{26}$$

Equation (26) represents the drop size in terms of the radial position, gas properties, mass of the drop and operating velocity. There are several interesting points to be noted in Equation (26) as follows. Drop sizes are found to be distributed nearly proportional to the radial position (i.e., $d \sim r^{0.75}$). Further, the derived correlation equation does predict the depencency of the average drop size upon the device dimension R and the flow characteristics such as air velocity u_o and the number of swirls inside the tube, S.

It should be pointed out that instead of using the number of swirls, S, included in Equation (25), one can also utilize the chamber length, L. In that case, the flow residence time in the chamber becomes L/w, where w is the axial flow velocity. In general, the axial velocity in a swirling flow decreases with an increasing radial position. Thus, the calculation results for this residence time would also yield an expression similar to Equation (25) in that the time spent by a drop increases with the increasing radial distance it travels. Thus, the chamber length, which is considered to be a more explicit design parameter, can replace the number of swirls if an analytic expression for the axial flow in a swirl flow is known.

Conceptual Design

Before incorporating the derived Equation (26) into a conceptual design, several assumptions that have been employed in the foregoing analysis should be noted. In order to satisfy an assumption of a point liquid source at the inlet as implicitly employed in the analysis, it is desirable to introduce a liquid jet through a small nozzle near the axis. It is anticipated that a very uniform and idealized swirling flow pattern in a real device may also be difficult to achieve. Other condiderations to be given in the design include that the flow upstream of the swirler be kept close to a laminar flow to avoid any turbulence effects which would

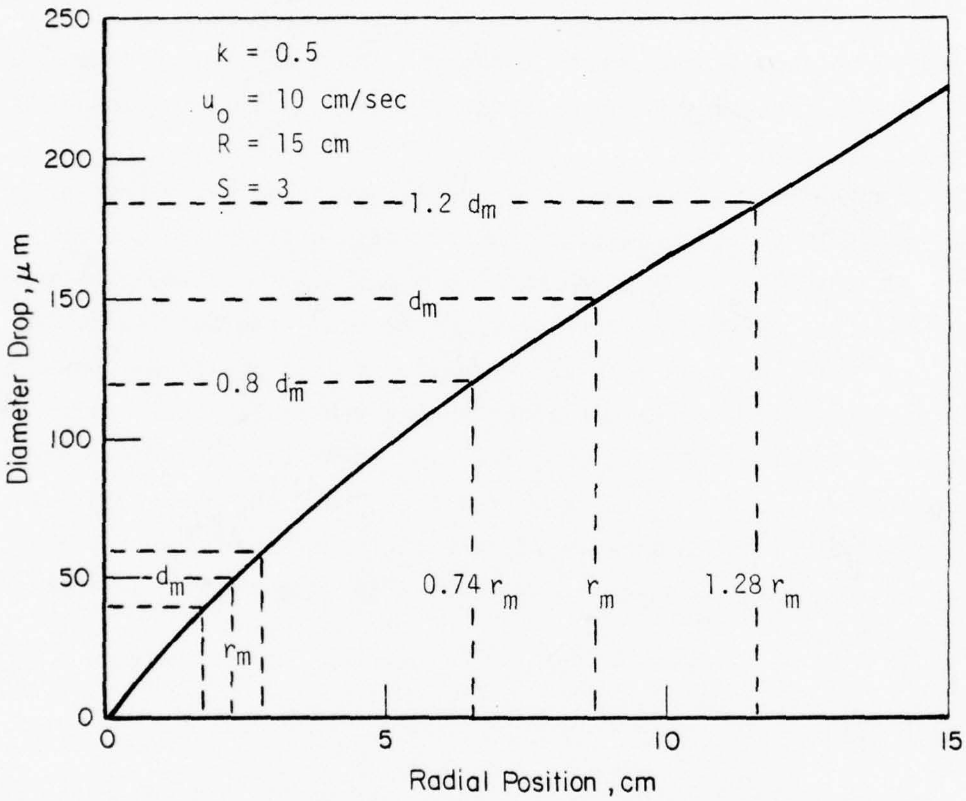

FIGURE 21. CALCULATED DROP SIZE DISTRIBUTION ALONG RADIAL DIRECTION AT EXIT

interfere with the trajectory of drops. As will be discussed later, dispersity of the drop size distribution of the spray will depend upon the choice of the annular section area from which the spray is ejected. For example, if a very narrow annular section is chosen, one would obtain a good monodisperse spray, while a spray chosen from a relatively large annular section would include a rather widely dispersed spray.

Based on the present principle, a preliminary calculation was made using the following data to examine the drop size of the spray produced by the technique:

$R = 15$ cm
$S = 3$ $\qquad \rho = 1\ \text{g/cm}^3$ (water)
$u_o = 10$ cm/sec $\qquad \mu = 1.84 \times 10^{-4}$ dyne-sec/cm^2 (air).
$k = 0.5$

The calculated drop size distribution as a function of radial position at the outlet is shown in Figure 21. It is seen that the average drop size ranges from 0 to 220 μm in diameter. Since the range of average drop size that is currently used in agricultural aviation application is about 25 to 500 μm, it is necessary to extend further the above size.

For this purpose, we can write an equation predicting the maximum particle size by setting $r = R$ in Equation (26):

$$d_{max} = 1.643\sqrt{\frac{\mu R}{kS\rho u_o}} \tag{27}$$

where d_{max} is the maximum drop size. Noting that μ and ρ in Equation (27) are the properties of air and liquid, respectively, one can increase the tube size R, decrease the velocity u_o, or decrease the number of swirls S in order to extend the maximum drop size. Using the data of $S = 3$, $\rho = 1$ g/cc, and $\mu = 1.84 \times 10^{-4}$ dyne-sec/cm^2, the dependency of the largest drop size upon flow velocity and tube dimension is shown in Figure 22.

Although Equation (27) can be used for a design criteria for extending the drop size range, the equation is not alone satisfactory if an extended flow rate is to be considered simultaneously. Therefore, a certain optimization becomes necessary. Effects of tube dimension and flow velocity on the flow rate, Q, are readily available from the following equation:

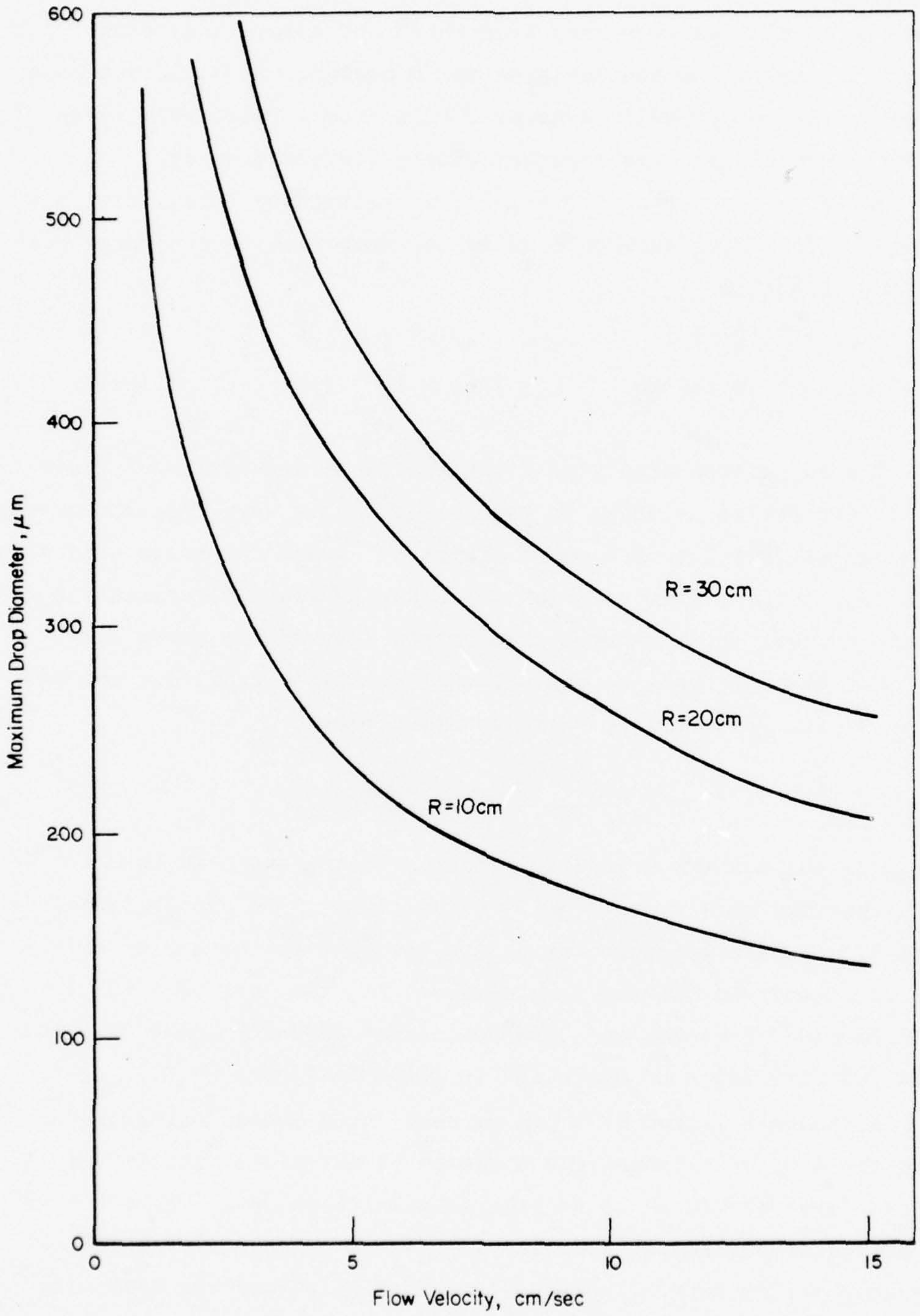

FIGURE 22. MAXIMUM DROP DIAMETER AS A FUNCTION OF FLOW VELOCITY AND CHAMBER SIZE

$$Q = \pi R^2 u_o \ . \tag{28}$$

Equation (28) suggests that in extending the drop size, an increase in the tube dimension is more beneficial than a reduction in flow velocity. However, such an increase may have to be restricted such that the resulting Reynolds number be kept small where possible.

Despite the above discussions on optimization, the tube size is further restricted since an excessively large tube cannot be mounted in an airplane. A tube radius of 30 cm is considered to be the largest dimension that can be realistically designed. If such a restricted increase in dimension does not extend the drop size sufficiently to meet the requirement, the large drop size has to be obtained by operating the device at a reduced velocity. Effects of reduced velocities and increased dimension-on the maximum drop diameter are shown in Figure 23.

In the present design, application rate of liquid material depends more or less upon the air flow rate which is determined by operating velocity and tube radius. Since a conventional twin fluid or liquid jet atomizer is to be used as a polydisperse spray source and located in a position near the center, the application problem also becomes a choice of a suitable atomizer. Another consideration to be given associated with the liquid application rate is that only a portion of the liquid disseminated from the atomizer is sprayed and the rest of the liquid drops which are not desirable in size are recirculated. Further detailed discussion will be made later.

Dispersion of drop size distribution of the spray produced by the current design can be controlled by adjusting the area of the selected annular cross section. The required drop size dispersion is such that 90 percent of the drops be within the range of 80 percent to 120 percent of the mean drop size. Since the drop size is distributed with a relation proportional to $r^{3/4}$ as shown in Equation (26), the outer and inner radii of the annular section should be $(0.8)^{4/3}$ and $(1.2)^{4/3}$ times the mean radius r_m or 0.74 r_m and 1.28 r_m, respectively. This is illustrated in Figures 21 and 23. However, if the incoming spray is nearly monodisperse, the above criterion would become less restrictive.

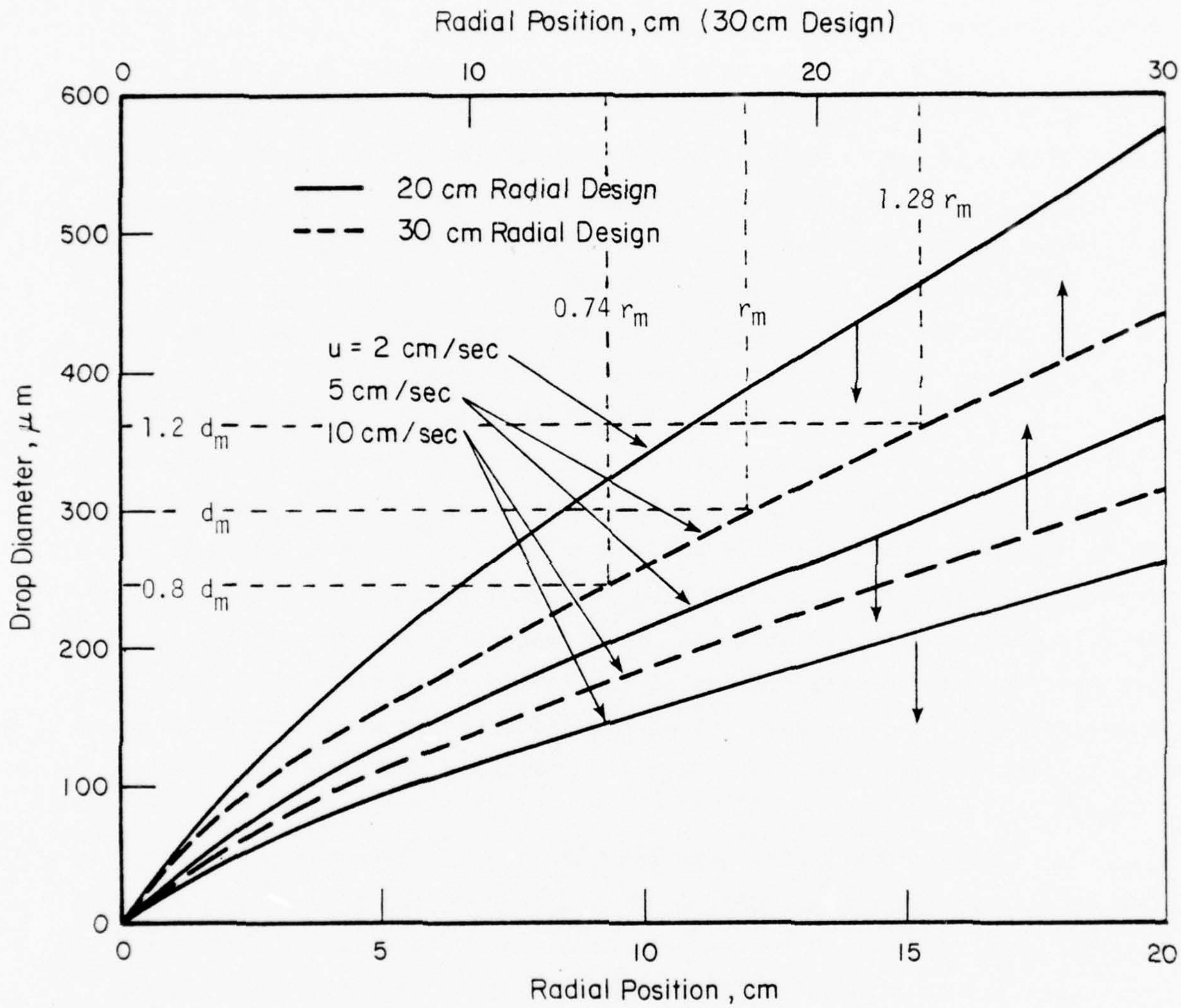

FIGURE 23. DESIGN CHART FOR CENTRIFUGE CHAMBER TYPE DROP CLASSIFIER

The only liquid property which affects size of the drops produced by the present design is the liquid density, as shown in Equation (26). As discussed previously, it was known that density of the commonly used liquid material in agricultural aviation application ranges from 0.8 to 1.25 g/cc. Noting that the drop size is inversely proportional to the square of the liquid density, the rather narrow density range of the liquid material that is currently used does not impose a significant problem.

Assessment of the Design

In this section, the proposed design is assessed in terms of its ability to cover the range of the average drop size, dispersion of the drop size distribution, application rate and operating range of liquid properties.

Average Drop Size Range. As discussed previously, the present design concept covers a wide range of average drop size depending upon suitable operating conditions and device dimensions. The particular design with 20 cm radius tube would produce an average drop diameter rangine from 0 to 300 μm, as demonstrated in Figure 23. For larger drop sizes, a 30 cm device, if operating at an air velocity of about 4 cm/sec, can achieve an average drop size up to 500 μm.

Dispersion of the Drop Size Distribution. As evident in the preceding analysis for the design, the dispersion of the drop size distribution can be controlled by adjusting the annular section from which a liquid spray is to be extracted. Since drop sizes are distributed along the radial direction proportionally to $r^{3/4}$, the monodispersity requirement can be satisfied by allowing the drops to leave an annular section whose outer and inner radii are 0.74 r_m and 1.28 r_m, respectively, where r_m is the radial position from which drops having average diameter, d_m, leave. It should be further noted that dispersion of drop sizes would not vary with changes in flow velocity or in liquid properties. According to the principle used in the design, the above assessment is theoretically correct. It is, however, expected that there would be some drop size resolution problems primarily

due to expected non-ideal characteristics of a swirling flow. Only fabrication and testing of the device can resolve the question regarding the real dispersion of the drop size distribution.

Application Rate. Although it is not known exactly how the device would perform, qualitative assessment of the application rate can be made as follows using engineering judgment. The liquid application rate of the present device depends primarily on the actual performance and operation, such as the application rate of the primary nozzle to be used and the operating air velocity. Further, the application rate is further affected by the cross sectional area of the annular section at the outlet. In general, it seems to be advantageous to use a liquid pressure type atomizer as a primary spray source due to its large capacity compared to twin fluid atomizers. Also, it is important to select an atomizer or operate the atomizer in such a way to produce a spray whose mean size closely matches the desired drop diameter. In other words, if a spray of relatively fine drops is desired to be produced using the present design, a primary atomizer producing a spray containing drops of such size is to be selected to increase the application rate.

Liquid Properties. Due to the principle of classifying liquid drops to different size categories using a centrifugal force, operation of the present design is not affected by any liquid properties (such as liquid viscosity, density and surface tension). Although operation is not affected by any liquid properties, the average drop size is affected by the liquid density, as shown in Equation (26). However, this is an operational condition rather than capability of the current device.

Suggested Development Work

Since the design of the centrifuge-type chamber is conceptual in nature, and since no supporting experimental data or performance information are available on the actual performance, it is only possible to discuss qualitatively the feasibility of extending this principle into a real means for producing a monodisperse spray.

Although the principle and the theoretical analysis have been established, one of the uncertainties associated with the present concept is an establishment or study of a uniform swirling flow as needed. A selection of a suitable rotating vane or the design of radially introduced air flow create a most desirable swirling flow needs to be studied. In conjunction with this, the simple formula shown in Equation (23) that was used in predicting a tangential velocity distribution as a function of the radial position must also be verified experimentally. The number of swirls that has been assumed for the purpose of theoretical development in this study is expected to vary depending upon the tube length and the type of rotating element to be used. Again this number of swirls should be studied in connection with flow patterns.

Although average drop size, range, dispersion of drop size distribution of the spray and effects of liquid properties were analytically well established, one uncertainty in actual performance of the present device is the liquid flow rate that can be covered. As already assessed, a selection of suitable atomizer and detailed geometric and fluid dynamic match experimentally between the atomizer and the current design remain as an area of further development.

Two Opposed Liquid-Laden Air Jets

When two air-liquid jets facing each other are operated, it is expected that there occurs an air flow stagnation region near the center and that flows are eventually directed radially. In addition, some instabilities can be expected in the flow. If the jets emerge from facing surfaces, one can expect standing waves to be set up such that wave frequencies are coupled with flow instabilities. As a result, liquid drops would experience sudden decelerated and accelerated flow while passing through air waves. Due to the difference in their inertia, large drops undergo more breakup stages than small drops. As a result, the drop size distribution of the spray will be made more narrow.

This concept can be considered an extension of the Hartmann whistle (1927,1939) or of another atomizer called the "Sonicore" nozzle.

In the Hartmann type atomizer, a jet of air is impacted on an axially positioned cup. With the cup within the proper range of distances from the nozzle, an intense first mode frequency is produced when the flow is sonic at the jet orifice. In the Sonicore nozzle (International Flame Research Foundation, 1978), the jet orifice is replaced with a convergent-divergent nozzle, and the liquid is injected in the direction normal to the flow through several orifices at the nozzle throat. In the present concept, two such nozzles are directed toward each other without a cup. It is expected that with the proper spacing of the jets and contour around each jet, a sonic generator will also result which is capable of breaking up the liquid spray.

Background

The lack of detailed analysis of this complex combination of a sonic generation and a liquid breakup has hindered both the use and improvement of the design. Studies over two decades ago found no significant change in spray size distribution when the sonic cup was filled in. That is, there was an indication that the sonic aspect of the nozzle might have no effect on the spray. However, in the absence of the specific report in which this widely reported study was made, it is not known to what air pressure level the data were taken.

Khandwawala, et al. (1974) reported results on mean drop size using the Hartmann acoustic generator to atomize three light oils, for pressures from 2 to 5 atomospheres and frequency from 5 to 22 kHz. There are some questions about their final correlation since the differences in density, viscosity, and surface tension were ignored. The jet exit diameter (equal to the cup diameter) was varied from 4 to 6 mm and included in the correlation, and the fuel burette was held constant in size. Nevertheless, the depth of the cup was varied in order to vary the frequency, and a wide range of pressures was used. These data showed that the Sauter mean diameter decreased with increasing frequency to about the 1/4 power, and decreased with increasing absolute pressure to the 4/3 power. The range of mean drop sizes obtained was 12 to 60 microns.

Recent tests of a Sonicore nozzle as reported by the International Flame Research Foundation (1978) using fuel oil at 9 to 19 centistokes showed the normally expected type of drop size distribution for gage pressures of 0.28, 0.35, and 0.71 bar, with mean drop size decreasing with increasing air pressure. However, at the gage pressure 1.41 bar the size distribution narrowed drastically, as illustrated in Figure 24. It is seen in the figure that the size distribution obtained at a pressure of 1.41 bar is sufficiently narrow to satisfy the requirements for an atomizer to be developed in this study. There appears to be a critical pressure at about 1 bar beyond which the drop size distribution suddenly becomes monodisperse, although this could not be positively ascertained.

In another recent study, not yet available in the open literature, the noise of Sonicore nozzles Nos. 035H and 052H were determined using water as the liquid. Up to 1.5 kilopascals, the noise output varied in a manner similar to that of usual jet noise (power $\approx$ pressure^3). However, when the pressure was further increased, there was a sudden break in the pressure-power data beyond which the noise power increased linearly with pressure. Measurements of linear mean diameter and Sauter mean diameter showed a significant decrease in the ratios for the two nozzles in going to the higher pressure region. The absolute values are not considered to be significant since there could be a consistent error in either undersizing the linear mean diameter or oversizing the Sauter mean diameter.

There appear to be two types of mechanisms that can enter into the spray production. For droplet distribution from the cross current breakup of a liquid jet of diameter d, in an airstream of velocity V, the following correlation equation for the volume median droplet diameter d_{30}, given by Ingebo and Foster (1957), is applicable for capillary wave breakup:

$$d_{30}/d_j = 3.9(\mathrm{We}\cdot\mathrm{Re})^{-1/4} , \qquad (29)$$

where

We = the Weber number = $\rho_g d_j V^2/\sigma$

Re = the Reynolds number = $d_j V/\nu$

σ = surface tension

ρ_g = gas density

ν = kinematic viscosity of liquid.

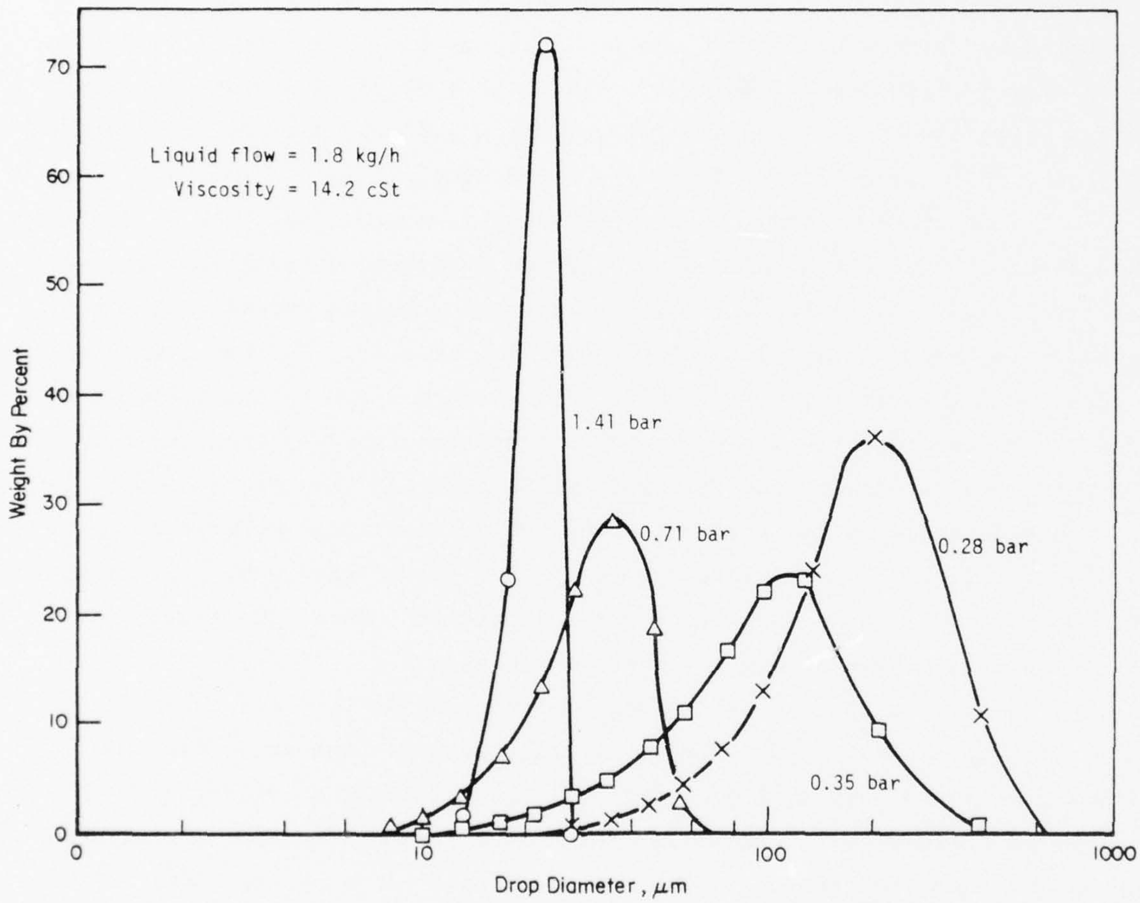

FIGURE 24. DROP SIZE DISTRIBUTION OF SPRAY PRODUCED BY SONICORE NOZZLE (International Flame Research Foundation, 1978)

A subsequent study showed that the above correlation was still valid even in an oscillatory gas flow at frequencies of about 100 and 1200 Hz providing the average value of the absolute relative velocity of gas and drop was used (Ingebo, 1966).

If a drop surface is exposed to an ultrasonic field, waves are set up in the surface. At sufficiently intense amplitudes, the waves will peak and tear off. Lang (1962) studied high frequency (9 to 80 kHz) atomization of both oil (27 mN/m, 850 kg/m^3) and water from deep pools and thin sheets on vibrating plates. From Kelvin's equation he notes that the wavelength, λ, of capillary waves is given by

$$\lambda^3 = 2\pi\sigma/\rho f^2 \, , \tag{30}$$

where σ is the surface tension, ρ is the liquid density, and f is the frequency of the waves. In terms of the sound generating frequency, F, we have

$$\lambda^3 = 8\pi\sigma/\rho F^2 \, . \tag{31}$$

Measurements agreed with these equations. The particle term from the wave tips correlated with

$$d_{10} = 0.34(8\pi\sigma/\rho F^2)^{1/3} \tag{32}$$

where d_{10} is the number median drop size. Analyzing Lang's one set of size data at 130 kHz for the mass median (50 percent mass) diameter, the constant appearing in Equation (32) is to be 0.43 rather than 0.34. Data were presented for 13, 130, 390 and 780 kHz.

When a drop is injected into a high velocity stream (which may be a shock wave or an acoustic wave), the drop is shattered. Studies have shown that this breakup comes from the distortion of the droplet by the drag forces, and this takes some time. Simpkins and Bales (1972) reviewed the work in this area. They pointed out that the droplets may break up by forming a bag-like shape at lower critical values of the Weber number or by viscous shear effects at higher values. However, a critical time is involved for the distortion to take place before the breakup starts. These authors use the Bond number [Bo = $\rho a r^2/\sigma$, where a is the acceleration and

r is the drop radius] to analyze their shock tube data. Obviously, Bo is related to We through Newton's law and the drag coefficient of the drop. They estimate the time for onset of unstable surface waves as given by

$$\left(\frac{\rho_g}{\rho}\right)^{1/2} \frac{U}{r}\, t = 22(\rho a r^2/\sigma)^{-1/4}$$

$$\cong 22(\rho U^2 r/1.25\sigma)^{-1/4} \qquad (33)$$

or

$$t = 196(2r/U^2)^{3/4} \quad \text{for water ,}$$

where r and U are in m and m/s, respectively. For breakup, about three times this time is estimated. Unfortunately, the drop size distribution of the breakup products is not reported in the literature.

The above phenomenon is related to the breakup of drops in a sound wave. A large droplet would flatten normal to the oscillation as the velocity oscillated in direction about the droplet. The flattened droplet would have waves built up in it that would result in a breakup in a controlled size range.

To summarize, there is no complete treatment of the Hartmann atomizing phenomenon. The Sonicore-type nozzle produces a broad, normal type of spray distribution at low pressure and a narrow spray distribution at higher pressures. It is considered that the change from one type to the other is related to a change in the noise output, which shifts from a jet noise to a monopole source-type noise. The ineffectiveness of the cup resonator may be a result of the rather low pressures employed in those experiments.

Therefore, if a critical oscillating shock wave system is built up and large drops are fed into it, these drops would be disintegrated into smaller droplets which would move out of the atomizing region with the general flow. The change in sharpness of the spray size distribution and the apparent coincidence with change in noise output characteristic suggests that the passage of the droplets through a small number of, or a single, shock front would not give the required narrow size distribution.

There is no doubt that a concentrated effort to understand the droplet breakup in this type of spray nozzle would result in a more useful and flexible design. For instance, one might control mean drop size by controlling the depth of the cavity.

Conceptual Design

Figure 25 shows a conceptual design developed based on the preceding discussions. This design can be used as a laboratory device for test purposes. Two identical, opposed nozzles are mounted so as to be adjustable in distance. With this arrangement, a sonic field will be set up between the facing plates surrounding the jets, and the frequency will be controlled by the spacing between the plates.

Figure 26 shows an enlarged view of the core of a jet system. Eight ducts feed liquid into the high pressure jet to eliminate any pattern of liquid flow. For the dimensions given, it is expected that the capacity would be of the order of 100 kg/hr, with mean droplet sizes adjustable from 20 to 80 microns.

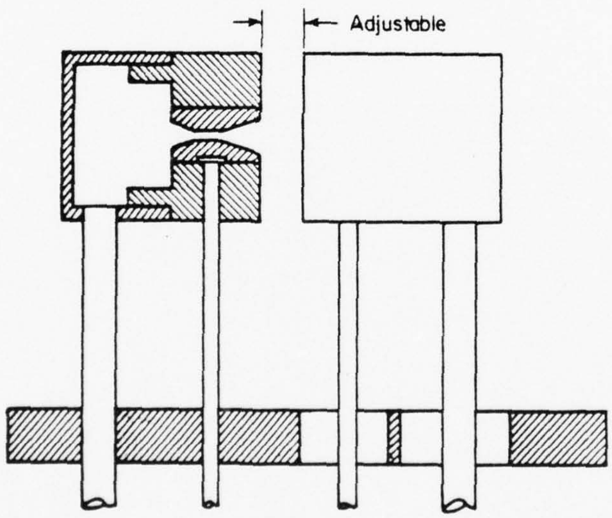

FIGURE 25. LABORATORY MODEL OF TWO OPPOSED LIQUID-LADEN AIR NOZZLES

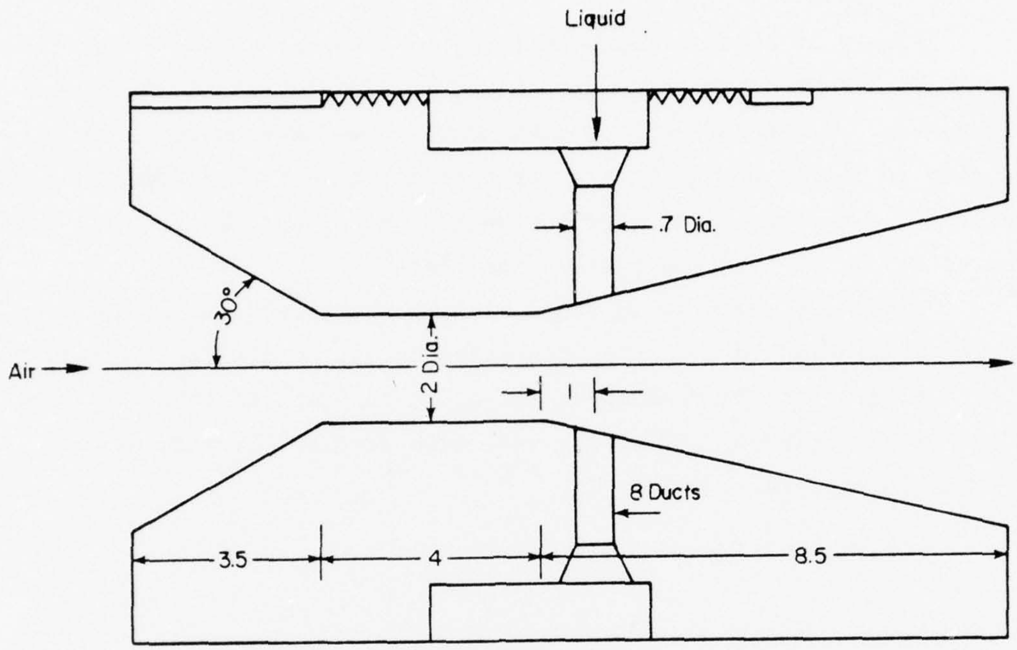

FIGURE 26. DESIGN DETAILS OF TWO OPPOSED LIQUID-LADEN AIR NOZZLES (Unit: mm)

Assessment of the Design

The assessment of the design concept is based on logical extrapolation of an array of experimental data as already discussed rather than on any basic theory of operation. On this basis, it appears that the range of mean diameter might be from 10 to 100 μm, with a possible 4:1 change in diameter for a single nozzle. The dispersion should be approximately

constant, with 5 percent above and 5 percent below the 80 percent to 120 percent of mean drop-size range. The available data indicate that kinetic viscosity from 0.25 mm^2/sec to 20 mm^2/sec can be handled. This covers from water to heavy oil. The design capacity of the proposed design is 100 kg/hr. Smaller capacities should afford no problems. However, larger capacities may be difficult to obtain, and multiple nozzles would be needed.

Suggested Development Work

The next logical step would be to build an experimental unit similar to that shown in Figure 25. First, the concept would have to be proved, and second, after proving the concept, work would proceed to examine the effect of the spray variables (air pressure, air flow rate, gap width) and fluid variables (viscosity, density, surface tension). Third, the effect of size changes in the new spray nozzle design would be examined. Fourth, one could concentrate on optimization by changes in fuel jet size, number and location, throat contour, and similar details.

Spinning Disk Coupled with Ultrasonic Field

It is well known that a very uniformly sized spray can be produced by a spinning disk, cup, cone or similar shape (Putnam, 1957, and Dunskii, 1965). However, as already discussed, one problem with this technique associated with the agricultural aviation applications is its limited application rate while maintaining good atomization characteristics. As the limited flow rate is increased, there is a range in which ligaments are produced from the disk rather than droplets. These ligaments then break up into more or less random lengths. At an even higher liquid rate, a sheet of fluid is formed. This eventually breaks up into drops of many different sizes. However, if these ligaments are subjected to an ultrasonic field or an electrostatic field they would break up into a spray of drops having uniform sizes. The exact breakup size depends on the ligament

diameter, the velocity, and the ultrasonic frequency in relation to the Rayleigh breakup of the ligaments. This procedure could provide a method of producing a more compact and higher flow rate spray of uniform size than could be achieved with a bank of spinning disks each operating at the typical low flow rates.

Although this concept originates from the concept of a conventional spinning disk, the two concepts are different in that the present concept concerns the region of liquid sheet formation and sheet breakup into uniform size droplets by use of an ultrasonic field. This can be done by imposing one frequency directly, or by using one frequency to produce ligaments above the normal ligament loading and then using a second frequency to break up the ligaments.

In conjunction with the present concept, it should also be mentioned that it is possible to use the sheet generated by two impinging jets. Huang (1970) showed that a maximum radius of the sheet before breakup was reached at a Weber number of about 800, at a ratio of sheet diameter to impinging jet diameter, d, of somewhat over 100. Ultrasonic action could be used on the sheet to finely atomize the fluid. Despite many possible schemes, as discussed, only the spinning disk method coupled with one frequency will be considered in this study.

Background

There is considerable information on the performance of conventional spinning disks and cups relative to the production of uniform sizes of drops plus satellites at low loads and on the production of ligaments with subsequent breakup at somewhat higher loadings. However, there has not been too much interest in the formation of sheets at the high loads. From Hinze and Milborn (1950) a relation is obtained predicting the flow rate at which there is a change from ligament to sheet flow, namely

$$(Q^2\rho/d_c^3\,\sigma)(\omega^2\rho d_c^3/\sigma)^{0.6}(\mu^2/\rho\sigma d_c)^{1/6} = 1.77 \qquad (34)$$

where d_c is the cup diameter and ω is the rotational speed.

For water, with a 5-cm cup rotating at $\omega = 10^3$/sec or 9500 rpm, supply rates above about 6 gph will give a sheet type flow. The average radial velocity is derived in the form

$$U_r = (\rho\omega^2 Q^2 \sin\theta / 6\pi^2 \mu d_c)^{1/3} \text{ m} \tag{35}$$

where the angle θ is between the edge surface of the cup and the axis (i.e., a disk gives 90 degrees). The manner in which waves are formed by the interaction of the high tangential velocity, low radial velocity, and the interaction with the air is not entirely clear. Further treatment of these phenomena is given by Fraser, et al. (1963) and reviewed by Dombrowski and Munday (1968).

In a related problem, the disintegration of liquid sheets from swirl chamber spray nozzles, both experimental and theoretical work have been reported. York, et al (1953) derived the growth rate equation for various wavelengths in a sheet moving relative to the surroundings and presented curves for air/water systems over a range of Weber numbers. Dombrowski (1968) reviewed this and other related work and found the wavelength of maximum growth, λ_{max}, was given by

$$\lambda_{max} = k\pi\sigma / \rho_g U^2 , \tag{36}$$

where $3 < k < 4$ over the entire range of conditions.

Clark and Dombrowski (1972) solved the same type of problem but emphasized the breakup of the sheet. Their theoretical relation generally predicted values of distance to the breakup region significantly below the observed values. This indicates that more surface might be available for controlled breakup than that expected from any present theory.

Concerning the breakup of this surface by an ultrasonic field, the work of Lang (1962) was already reviewed in a previous section. It is interesting to note, however, that if one limits the ultrasonic range to frequencies of 20 kHz or more and considers water ($\sigma = 73 \times 10^{-3}$ kg/sec^2), the maximum value of the number median droplet size is 56 microns. If a larger median diameter is desired, either the frequency will have to be reduced and muffled, or an alternative approach such as the use of electrostatic effects would have to be used.

Conceptual Design

Figure 27 shows the conceptual design for the ultrasonic atomization of a liquid film. The liquid film, exposed to the ultrasonic field on both sides, is produced by a spinning cup, overloaded considerably beyond the usual range in which droplets or ligaments are produced but not sufficiently to prevent a large free sheet area from being formed. The ultrasonic field is produced by a horn in the arrangement shown in the figure. A rod with a flexing annular ring might also be considered. An intense standing wave is set up between the horn surface and the reflecting plate. Adjustment is necessary to optimize the system experimentally for the driving frequency and the appropriate location of the fluid film in the interspace. A small amount of air is to be supplied (natural aspiration might be sufficient) to prevent a pressure buildup that could produce an instability in the fluid film.

It is difficult to estimate the load capacity of this design primarily due to lack of existing experimental data on the variation of free liquid sheet size as a function of loading, cup size and rpm. It is felt that the above design should be good to 10 gph, and possibly a much larger capacity.

Assessment of the Design

In this design concept, the median drop size is determined by Lang's (1962) relation. For water, the drop size is 56 μm at 20 kHz, and decreases with increasing frequency; Lang shows data to less than 4 μm. If an acoustic silencing means is adopted, then the low frequency end could be extended. The median drop diameter, which varies with $f^{-2/3}$, could be increased to larger sizes. The median drop diameter is affected less by surface tension and density, varying with $(\sigma/\rho)^{1/3}$.

It is rather difficult to predict a dispersion of drop size distribution of the spray obtained without operating the optimized device. Lang's data indicate a dispersion larger than that desired. In one set of

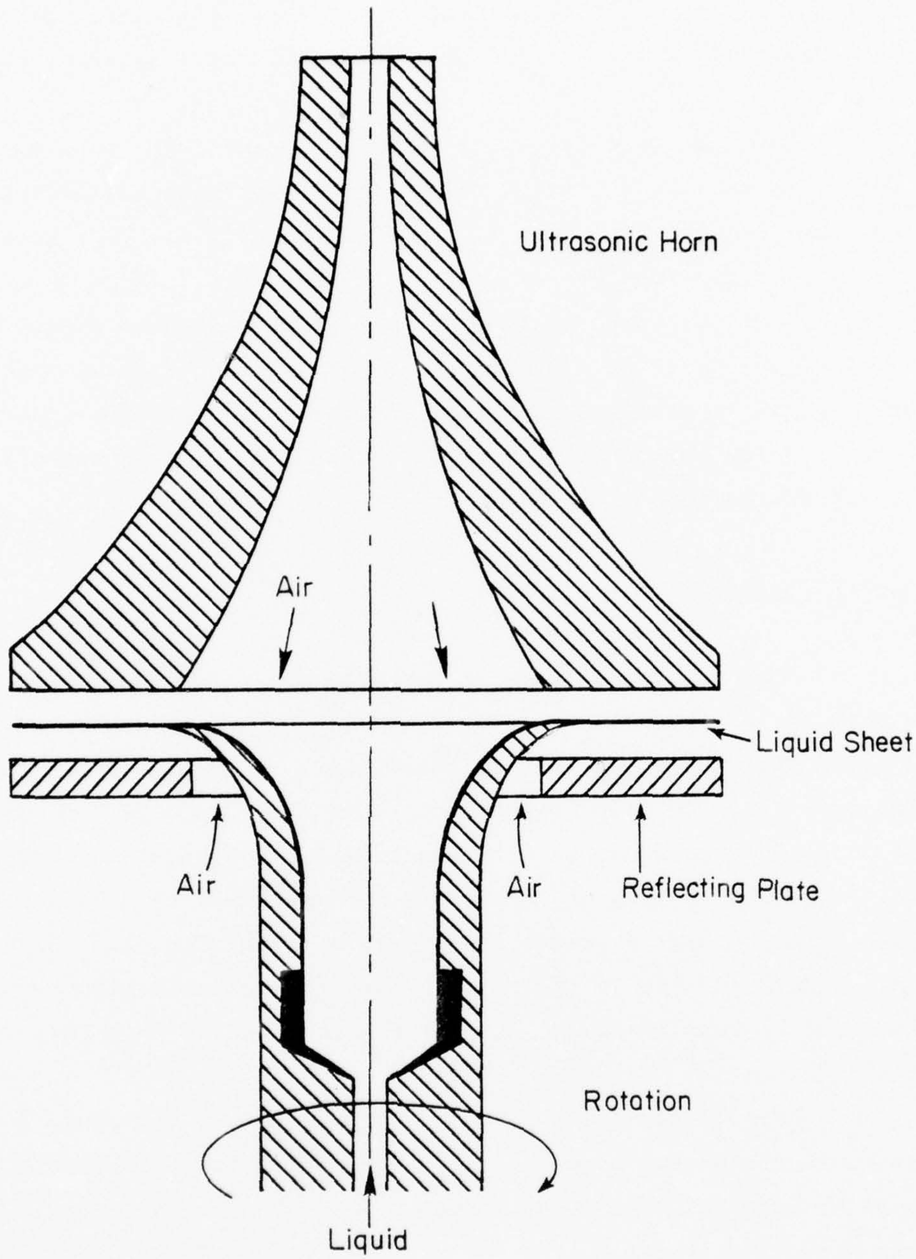

FIGURE 27. DESIGN CONCEPT OF ULTRASONIC ATOMIZATION OF A LIQUID SHEET PRODUCED BY SPINNING-DISK METHOD

data, for instance, only 80 percent of the spray was within a 2:1 diameter range. However, it is expected that this range of dispersion can be reduced.

The liquids that can be sprayed should cover properties typical of water, light oil, and heavy oils. The amount that can be sprayed cannot be deduced from the available data. It will certainly be greater, and probably by a considerable amount, than the amount at which a sheet starts forming in preference to ligaments. With the particular design given above, this is 6 gph for water. If the extent of the liquid sheet before normal breakup could be obtained from the literature, the maximum load would then be equal to the number of wave cells on the two surfaces times the drop size and the frequency.

Suggested Development Work

Once the concept for the present approach has been established, the next logical step is to fill in the gap in the literature concerning the spray sheet produced by a spinning disk. A small number of spinning disks would suffice. It is suggested that they would be run mainly with one fluid, with short tests on a few additional fluids to determine the effects of surface tension, viscosity, and density. The main tests should relate breakup sheet diameter to flow rate, disk size, and speed of rotation. Mean drop size of the spray after breakup would also be determined. This would be related to the mean drop size expected when the ultrasonic (or electrostatic) field was imposed.

Upon obtaining these data, the effect of ultrasonic fields of various strengths and frequencies on the median size and size distribution should be experimentally determined.

COMPARISON OF PROPOSED TECHNIQUES

As already assessed, the three proposed designs are exploratory in nature primarily due to lack of supporting experimental data or operating experience. Consequently, it would not be very meaningful to attempt to evaluate or directly compare these theoretical techniques. For this reason, only the degree to which each of the proposed designs is expected to meet the specified performance requirements is summarized in Table 9.

TABLE 9. SUMMARY OF CAPABILITIES FOR PROPOSED TECHNIQUES

	Capabilities for Proposed Techniques		
Requirements for Techniques	Centrifuge Type Chamber	Two Opposed Liquid-Laden Air Jets	Spinning Disk with Ultrasonic Field
Sprays, nearly monodisperse[a]	Can produce a very narrow drop size distribution	90 percent within 80 to 120 percent of mean diameter	Better than that obtainable by an existing ultrasonic atomizer
Average Drop Size, 25 - 500 μm	0 - 600 μm	10 - 100 μm for an experimental unit	Up to 200 μm; could be extended
Application Rate, 5 - 50 ℓpm (Single unit)	Depends upon flow rate of primary atomizer used; expected to be satisfactory	Low rates for an initial experimental unit; can be extended	10 gph for laboratory scale
Liquid Properties: Density, 0.8 - 1.25 g/cc; Viscosity, 0.3 - 500 cp; Surface Tension, 20 - 80 dyne/cm	Liquid properties have no effect on operation	Operates on most liquid materials	Surface tension and density are important parameters
Future Development Area	Flow pattern in the chamber needs to be studied; match between aircraft speed and operating air flow desirable.	Feasibility study and performance evaluations needed on a laboratory scale.	Experimental verification needed; experimental match between liquid sheet size and frequency to be determined.

(a) Five percent by weight of the drops can be larger than a maximum size and only 5 percent smaller than a minimum size where the maximum and minimum are 1.2 and 0.80 times the average diameter, respectively.

CONCLUDING REMARKS

As a result of the first phase of the present program, about fifteen different techniques for producing sprays have been identified. Among the identified techniques, five techniques which were found to be capable of producing a monodisperse or nearly monodisperse spray have been closely studied and compared with each other. The result of this comparison is that periodic dispersion of liquid jet, spinning disk method, and ultrasonic atomization have been found to be most promising. While these techniques can provide a monodisperse spray over a reasonable range of average drop size, all of them require some extension of their flow rate capabilities to match those required for the purpose of agricultural aviation applications.

Additionally, three conceptual designs of atomizers for producing a monodisperse spray have been generated. Where possible, a theoretical equation which predicts the performance of each device has been obtained employing certain simplifying assumptions. Due to the exploratory nature of the present program, no available experimental data or test experience associated with these new concepts exist. Consequently, it is considered difficult to evaluate these concepts definitively at the present time.

For further development of the generated conceptual techniques into a practical unit, it is considered necessary to evaluate the soundness of each approach by means of experimental tests. Since each of the proposed designs is based on a new concept, such experiments should be aimed at validation and further development of the basic principles rather than at a direct application for use. Therefore, laboratory scale experiments would be more meaningful than full scale experiments.

In conjunction with the results of the first phase of the study, the existing techniques that were identified as very promising should also be given consideration. Of these identified techniques, the principle of periodic dispersion of a liquid jet is recommended for development into an atomizer for eventual agricultural aviation use.

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